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ATC ACCOMODATION OF FUEL CONSERVATIVE TURBOJET OPERATIONS.(U)

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ATC ACCOMMODATION OF FUEL CONSERVATIVE TURBOJET OPERATIONS.

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16. Abstract

This study estimates and compares the fuel savings potential of each of five fuel conservation ideas which, if adopted, would require significant changes to the Federal Air Regulations or in the way the air traffic control system operates. The five ideas are (1) absorb landing delays before leaving en route airspace, (2) permit cleaner, higher speed approach and landing procedures, (3) lower the altitude restriction on the 250 knot speed limit in TCAs, (4) increase the number of flight levels above 29,000 feet, and (5) eliminate fixed cruise or crossing altitude restrictions.

Comparative estimates of the fuel-saving potential of each of these ideas are developed, both on a per-flight basis and on an annual national basis. For three of the more promising ideas, the potential implementation problems and possible solutions are identified and explored.

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The authors, of course, assume full responsibility for ways in which the data provided by these organizations and individuals is used and interpreted in this study.

EXECUTIVE SUMMARY

This study examines five ideas for conserving aviation jet fuel. These five ideas are of particular interest because of the potential of each to:

1. save significant amounts of fuel on either a per-flight basis, or on an annualized basis due to the large number of flights nationally that could potentially benefit, and to

2. cause significant changes to be made in either the Federal Air Regulations or in the way the air traffic control (ATC) system operates. These changes can range from procedural and ATC automation improvements on the ground to possibly more stringent requirements on aircraft operators.

Table 1 lists these five ideas and the estimated fuel-savings potential of each, both on a per-flight basis and on a national annual basis. The fuel burn characteristics of the Boeing 727-200 series aircraft are assumed to be representative in analyzing all ideas, but one (number 4, in Table 1). In that case, a weighted average of the B727-200 and the L1011 was taken, since the wide-body burns could not be assumed to be balanced by a large number of DC9 and B737 operations.

The perspective, argument, and results of the examination of each of these ideas is summarized in the order of Table 1. Conclusions and Recommendations follow this summary.

TABLE I

ESTIMATES OF THE FUEL SAVING POTENTIALS OF THE IDEAS CONSIDERED

	BASIS FOR AVERAGE FLIGHT FUEL SAVING	FUEL SAVINGS PER AVERAGE FLIGHT (GALLONS)	FLIGHTS WHICH MIGHT BENEFIT ANNUALLY[e] (MILLIONS)	FUEL SAVINGS ANNUALLY[b] (MILLIONS OF GALLONS)
1. ABSORB LANDING DELAYS BEFORE LEAVING EN ROUTE AIRSPACE				
Fixed-Gradient Profile Descents - No Speed Control				
No Competition for Runway	Denver profile descent vs step-down descent.	108	3.0	From 324
13% Loss of Runway Throughput	Computer simulation of landing delays as a function of throughput.	0	---	
Variable-Gradient Profile Descents - Speed Control for Delay Absorption				
In Cruise + Idle Thrust Descents In Cruise + Reduced or Idle Thrust Descents	Distance of 115 miles from FL350 to the downwind leg for the runway; average of fuel burns for steepest and shallowest descent profiles, including level segment.	86 133	4.5 4.5	387 To 598
2. PERMIT CLEANER, HIGHER SPEED APPROACH PROCEDURES				
Delayed Flap, No Significant Delays Delayed Flap, Significant Delays	As reported by Boeing study (Reference 1-4) Runway capacity model	50 May Drop	4.5	To 225 (If no Drop)
Reduced Flap, No Significant Delays Reduced Flap, Significant Delays	As reported by Boeing study (ibid) Runway capacity model	12 May Drop	4.5	From 54 (If no Drop)
3. LOWER THE ALTITUDE REQUIREMENT ON THE 250 KNOT SPEED LIMIT				
In TCAs, To below 3,000 Feet for Departures In TCAs, To below 5,000 Feet for Arrivals (No Landing Delay)	Fuel burn model for B727; also analysis of Chicago profile descent procedures	15 5 20	2.4 0.9 3.3	36 4 40
4. INCREASE THE NUMBER OF FLIGHT LEVELS ABOVE FL290				
1,500 Feet Separation, FL290 - FL395 or 1,000 Feet Separation, FL290 - FL330	All flights of 200 miles or more are assumed to cruise at the flight level nearest the optimum altitude for the aircrafts' current gross weight (traffic not a factor)	6.7[a] 14.7[a]	1.8 0.7	To 12 From 10
5. ELIMINATE FIXED CRUISE OR CROSSING ALTITUDE RESTRICTIONS				
Between Washington, D.C. & New York Only Nationally	LGA to DCA at 24,000 feet instead of 16,000 feet Other cases cited, but not analyzed.	81 (Not Estimated)	0.04 (Not Estimated)	From 3 To ?
				From 431M (5%)[c] or $151M[d] To 875M +? (10%)[c] or $306M[d]

[a]Weighted average for B727 and L1011.

[b]Assumes that the single-flight case analyzed is a representative average for all flights assumed to benefit annually.

[c]Percent of the FY76 jet fuel burn (8.4 billion gallons).

[d]At 35¢ per gallon.

[e]Appendix C

1. ABSORB LANDING DELAYS BEFORE LEAVING EN ROUTE AIRSPACE (CHAPTER 2)

When there is no competition for the use of the runway, profile descent procedures* are shown to have the potential for saving significant amounts of fuel, relative to the "step-down descent" procedures they typically replace. But when there is sustained competition for the runway, it is also shown that small, perhaps imperceptible, losses in runway throughput can significantly increase average landing delays and thus cause significant amounts of excess fuel to be consumed. The two subjects, profile descent procedures and runway throughput losses, are related because en route metering procedures are being developed and implemented to anticipate and absorb landing delays before the arriving aircraft begin their profile descents into the terminal area. If en route metering is not properly done, runway throughput can easily be lost.**

Profile Descent Fuel Savings, Given No Runway Competition:

A particular profile descent procedure at Denver is compared to the step-down descent procedure previously used and is found capable of saving over 100 gallons of fuel per descent, when other traffic is not a factor (Section 2.1). The profile descent is assumed to be conducted without significant level-offs or applications of power from 35,000 feet MSL to the final approach couse, while the step-down descent is assumed to be conducted at a higher speed and along a much steeper descent gradient, so as to meet an altitude crossing restriction at the ARTCC-TRACON boundary.*** In the latter case, the aircraft must level off,

* Profile descent procedures have been designed to permit the execution of uninterrupted descents from the beginning of the en route descent down to the final approach course for the runway. The intent is to minimize turbojet flying time below 10,000 feet (above airport elevation) and to maximize the conversion of the potential energy of altitude into the kinetic energy required to reach the runway. Thrust is normally applied only to achieve a stabilized approach speed and to insure separation from other aircraft, if required.

** The loss in throughput being referred to here is for the aircraft involved in the profile descents. That is, if runway throughput is kept up by inserting local arrivals into the traffic gaps, the fuel benefit of the profile descents is still lost to the aircraft using them.

*** Some of the problems associated with lifting altitude crossing restrictions are addressed in Chapter 6.

decelerate, and fly 25 miles or so with power on, at or below 12,000 feet, thus consuming the extra fuel. Had this descent been conducted to a sea-level airport (instead of mile-high Denver), another 5 gallons could have been saved.

Profile Descent Fuel Savings, Given Runway Competition:

A computer simulation was used to examine the effects of the loss of runway throughput which might result from fixed profile descent procedures. It was found that a 13% loss in runway throughput could cause the average landing delay to increase enough to offset all of the single-flight fuel savings (Section 2.2). In the case examined, this occurred when 30 aircraft were landing in an hour, instead of the 35 aircraft which could have been landed.*

When there is competition and landing delays must be absorbed, it is shown to be fuel-efficient to absorb a portion, but not all, of these delays before leaving the en route altitudes. The reason for not taking all predicted delays at high altitudes is that the penalty for delaying aircraft unnecessarily, thus reducing throughput, is shown to be much greater than that from absorbing any residual needed delays at low altitudes (Sections 2.2 and 2.4). To be successful, any metering strategy should discount its landing delay estimates by the uncertainty associated with that strategy's ability to accurately predict and absorb the right amount of delay. Sufficient control capability should be retained in the terminal area to absorb any residual delay needed later for final sequencing and spacing to the runway.

A logic for a metering strategy to absorb discounted landing delays en route using along-course speed reductions, especially during en route descent, is outlined in Section 2.3. It is shown that such a procedure offers a fair amount of delay absorption capability: up to five minutes within 135 miles of the runway. It is also fuel-conservative: over 100 gallons can be saved, relative to step-down descents, using variable-gradient descent profiles flown at idle or reduced thrust.

The advantage of such a procedure is that it provides for some delay absorption capability, without adding extra miles to the route and while retaining the fuel-conservative aspects of profile descent procedures. Discounted delays in excess of the

* The demand in this hour equaled 35 arrivals and was distributed uniformly across the hour. Effects of demand peaking were not examined.

controllability obtained through speed reductions can be absorbed in holding patterns. Since speed control is more accurate delay absorption tool than holding, the holding fixes for working off discounted delays should lie upstream, rather than downstream, from the first speed control point.

To form an estimate of potential fuel savings annually, fixed-gradient profile descent procedures are assumed to be fuel-efficient during periods of low-to-moderate runway demand (3 million operations annually), but not during periods of high runway demand (1.5 million operations annually). Variable-gradient profile descent procedures, which permit the use of speed control for metering and spacing descending arrivals, are assumed to be fuel efficient for all 4.5 million turbojet operations annually. In Table 1, fixed-gradient procedures are estimated to have a annual fuel saving potential of over 300 million gallons, while variable-gradient procedures have a 400 to 600 million gallon potential.

2. PERMIT CLEANER, HIGHER SPEED APPROACH PROCEDURES (CHAPTER 3)

Conventional ILS approach and landing procedures would typically have the aircraft level at about 1000 feet (above field elevation) and at a stabilized airspeed prior to glide slope capture and intercept. At the intercept (about 6 miles from the runway), landing flaps and gear would be lowered and a stabilized landing speed would be established.

In the interests of fuel conservation and noise abatement, "reduced-flap" and "delayed-flap" approach procedures have been developed. Reduced-flap procedures have been defined by the Air Transport Association and adopted in some form by most airlines. Delayed-flap procedures have been developed and flown experimentally by NASA and its contractors. Both procedures result in a higher initial approach speed, not necessarily stabilized, and some delay in the achievement of a stabilized landing speed. Delayed-flap procedures as developed by NASA depend upon having DME at the runway and special equipment on-board the aircraft. Published results on these procedures have been predicated on a 3000 foot glide-slope intercept (about 9 miles from the runway).

Fuel Savings, Given No Competition for the Runway:

The potential fuel saving from the use of delayed-flap procedures, relative to the more conventional procedures, is reported elsewhere to be about 50 gallons per approach for a B727-200 in "no wind" conditions (Reference 3-4). This saving is about one-third of the total conventional fuel burn over the last 40 miles to the runway. The saving is reported to more than double in a 30 knot headwind.

The potential fuel saving from the use of reduced-flap procedures which are typical of current airline practice is reported to be about 25% of that attainable using delayed-flap procedures, at least in "no wind" conditions (ibid).

Possible Impacts on Automated Metering and Spacing (M&S) Systems:

Automated metering and spacing systems have been designed to aid radar approach controllers in delivering aircraft to the final approach course with precise spacings between them. Precise spacing is desired during periods of high demand in order to maximize runway throughput, and thereby minimize landing delays and fuel burns. To date, the design of such systems has been predicted upon conventional ILS approach procedures. It is of interest to ascertain the potential impacts of the higher speed approach procedures on the design and performance of such systems.

Possible Impact on M&S System Design:

In theory, the establishment of higher initial speeds for the final approach course will reduce the amount of controllability achieveable in the terminal area for final sequencing and spacing. The amount of speed control is reduced by raising the lower limit on permissible speed reductions. The amount of path adjustment through vectoring is limited by the larger turns at the higher speeds that must be accommodated.

To get an idea of how significant the impact might be, a particular control geometry designed for an automated M&S system at Denver was examined. To retain as much controllability as possible, the vectoring area was expanded to the limits of available air space. Despite the expansion, 100 seconds of controllability (out of 270 seconds) was computed to be lost for aircraft conducting delayed-flap procedures, assuming that the minimum speed increases from 160 knots IAS (conventional) to 220 knots IAS (delayed-flap) and that the maximum speed remains at 250 knots. For the same comparison using reduced-flap procedures (minimum vectoring speed equals 180 knots IAS), 40 seconds of controllability was lost. Thus, due to airspace constraints, re-design of the control geometry could not fully compensate for the impacts on controllability of the higher speed procedures (Section 3.4).

Possible Impacts on M&S System Performance:

In theory, higher speeds along the final approach course could either increase or decrease runway throughput during periods of high arrival demand. Throughput could increase if higher average speeds to the runway threshold could be maintained without

incurring larger spacings between aircraft. However, larger spacings will be required to insure that separation standards are not violated, thus reducing throughput. Larger spacings will occur to the extent that either the range or the frequency of speed differences between successive aircraft is increased by introducing the higher speed procedures.

Another factor to consider is whether or not the last merge point onto the final approach course must be moved further away from the runway to accommodate a higher glide slope intercept. Moving the last merge point farther away will cause the aircraft to fly longer distances without further spacing control by ATC. Reference 3-6 suggests that the higher intercept is unnecessary, but all other published results available to the authors used a 3000 foot intercept (over 9 miles from the runway), instead of an 1800 foot intercept (about 6 miles from the runway). Moving the last merge point farther from the runway will increase the effect of speed differences on the inter-arrival spacings.

To get an idea of how the possibly longer common path and the wider range or frequency of speed differences might impact runway throughput, an existing computer model for estimating runway capacity was exercised. With due regard to the limitations of applying that model to this problem, it appears that:

1. The longer common path would reduce the potential arrival throughput by one or two landings per hour when reasonable mixes of aircraft types, or mixes of approach speed profiles for the same aircraft type, or mixes of both are assumed. Only in the special case of homogenous arrivals (100% large turbojet transports, all of which are equipped for and are conducting delayed-flap approaches) was the higher speed along the final approach couse able to compensate for the effect of the longer common path on throughput. (Section 3.5).

2. The higher speeds may or may not significantly affect potential arrival throughput, given that a higher glide slope intercept is not a constraint. It was found that the results are sensitive to speed profile and speed mix assumptions, and that the computer model used does not permit sufficiently accurate representation of unstabilized approach procedures to permit a more definite answer.

Higher Speed Approach Procedure Fuel Savings, Given Runway Competition

It is shown that as demand approaches capacity, small losses in runway throughput can negate the potential fuel savings of the higher speed approaches. In an assumed case, all fuel savings of reduced-flap approaches are shown to be lost to increased landing delays when throughput has been reduced by two aircraft per hour when demand equals capacity. This occurs in spite of the fact that an en route metering capability was assumed to derandomize and synchronize arrivals with a feeder fix delivery accuracy of one minute (one sigma). The delay picture would be worse if totally random arrivals had been assumed (Section 3.6).

On an annual basis, all 4.5 million turbojet operations could potentially benefit from cleaner, higher speed approach procedures, but only if procedures are developed to prevent any loss in runway throughput as demand approaches capacity.

3. LOWER THE ALTITUDE RESTRICTION ON THE 250 KNOT SPEED LIMIT WITHIN TCAs (CHAPTER 4)

Regulations now prohibit speeds in excess of 25 knots indicated below 10,000 feet MSL for safety reasons. Were it not for this restriction, turbojet departures might be able to climb out more quickly to the higher altitudes, and turbojet arrivals might postpone slowing to 250 knots until required for sequencing and spacing to the runway. Some fuel savings would result from reducing the time spent at the lower altitudes and speeds. The lower the elevation of the airport, the greater the savings.

This study calculated the potential savings for regular body turbojets (B727s) operating at higher speeds to/from sea level airports and 10,000 feet MSL:

1. to range between 10 and 20 gallons on departure, and to be

2. less than 10 gallons on arrival, assuming no landing delays.

In addition, a minute or two of flight time could be saved, assuming no traffic delays.

To analyze this benefit, the assumption is made that the altitude restriction might be lowered on the speed limit to 5,000 feet AGL,

without significant loss of safety, within Terminal Control Area (TCAs).* On this basis, the 2.4 million turbojets that are estimated to arrive and depart TCA-served airports annually could potentially benefit.

The fuel savings is calculated to average between 15 and 20 gallons per aircraft (5 on arrival if no landing delays, plus 15 upon departure). On this basis, 36 to 40 million gallons of fuel might be saved annually.

4. INCREASE THE NUMBER OF FLIGHT LEVELS ABOVE FL290 (CHAPTER 5)

The vertical separation between adjacent flight levels above FL290 is now 2000 feet. If the separation could be reduced, without loss of safety, then the opportunity for requesting and being assigned to a flight level nearer to the aircraft's current fuel-optimum altitude would be enhanced. First, the reduced vertical separation minimizes the possible difference between the best flight level and the aircraft's fuel-optimum altitude (may lie between flight levels). Second, if there is competition for flight levels between aircraft using a particular route, then adding flight levels would add capacity and reduce competition.

In this study, it is assumed that one additional flight level might be added each way by either reducing the required vertical separation to 1500 feet between FL290 and FL395, or by reducing it it 1000 feet between FL290 and FL330. The potential fuel savings were calculated on the assumption that all medium and long haul flights** would cruise at the most fuel-efficient flight level and speed for their current gross weight, and that competition for those flight levels would not be a significant factor.*** In particular, the heaviest aircraft would not

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* If necessary, TCA ceilings ould be raised to 10,000 feet MSL as it is now at Atlanta.

** Flight with stage lengths in excess of 400 nmi.

*** Under the assumption that competition for en route flight levels is a factor, some flights might be forced to operate at the next flight level below the most fuel-efficient one. For example, with the current 2000 foot separation, such flights would be displaced by 4000 additional feet, resulting in a significant additional fuel penalty. However, the percentage of such flights penalized annually by competition with same-way level traffic is thought to be small, at least over the Continental United States.

cruise above FL330 (B727s greater than 165 Klbs, or L1011s greater than 350 Klbs). On this basis, the potential fuel savings were found to be:

1. <u>For the reduction from 2000 feet to 1500 feet (FL290 - FL395)</u>: 4.85 gallons for the average regular-body flight (a B727 with 690 nmi at cruise altitude), and about 16.4 gallons for the average wide-body flight (an L1011 with 1495 nmi at cruise altitude). Assuming that 13% of all flights at these altitudes are wide-body, the weighted average fuel savings is 6.3 gallons per flight.

2. <u>For the reduction from 2000 feet to 1000 feet (FL290 - FL330)</u>: 11.0 gallons for the average regular-body flight and 39.3 gallons for the average wide-body flight. Assuming that 13% of all flights at these altitudes are wide-body, the weighted average fuel savings is 14.7 gallons per flight. The increase in per-flight savings is due to (1) the greater separation reduction and to (2) the fact that the heaviest aircraft are the ones to benefit.

About 1.8 million flights annually have stage lengths in excess of 400 nmi. Of these, about 37% were found to cruise between FL290 and FL330. On this basis, the potential annual fuel savings are calculated to be 12 million gallons for the 1500 feet reduction, and 10 million gallons for the 1000 feet reduction. The greater per-flight savings of option (b) were more than offset by the greater number of flights potentially benefiting from option (a).

5. <u>ELIMINATE THE NEED FOR FIXED ATC ALTITUDE RESTRICTIONS</u> (CHAPTER 6)

ATC often finds it necessary to segregate potentially conflicting traffic flows procedurally by fixed crossing or cruise altitude restrictions.

If improved means for predicting and resolving such conflicts on a real-time basis could be developed, then the desired altitudes might be time-shared by the conflicting flows. Altitude restrictions, or other separation procedures, would be imposed only as actual time and altitude coincidence predictions warrant.

The potential fuel savings are highly dependent upon specific circumstances and should be evaluated on a case-by-case basis. This study examined the case of restricting short-haul flights between Washington, D.C. and New York to the low altitude

structure. Analysis revealed that 108 scheduled flights each weekday, predominately B727s and DC9s, are affected.

Taking the LaGuardia to Washington, D.C. route as typical, the potential fuel saving per B727 flight was found to be 81 (or 88) gallons if FL240 (or FL260) could be assigned, rather than the current restricted altitude of 16,000 feet MSL. This translates into a calculated annual savings of over 3 million gallons annually for the 108 affected daily flights.

The potential problems with permitting these restricted short-hauls to enter the higher altitudes include:

1. Clearances with Potentially Conflicting Crossing Traffic would have to be Dynamically Generated and Coordinated

A sampling of the rate of crossing conflicts with the LaGuardia to Washington National route suggests that the desired altitudes would be available 40 minutes out of each hour. The crossing traffic is typically transitioning between the high altitude structure and the New York area. Given the present level of NAS Stage A automation and control procedures, it appears difficult to manually plan and coordinate these clearances with any accuracy and without incurring an unacceptable controller workload penalty. However, adding the ability to automatically predict the existence or absence of conflicts at the desired altitudes, to compute the highest available altitude when conflicts exist, and to automatically coordinate clearances with the high altitude sector would appear to solve this problem.

2. Merges with High Altitude Arriving Traffic would have to be Accomplished Earlier and/or at Higher Altitudes

These short-hauls are now typically merged with arrivals from the higher altitudes during level low altitude segments just prior to the terminal area feeder fix. To be fuel-conservative, both these short-hauls and the higher altitude arrivals would prefer to remain at higher altitudes longer. This means that the merging of this traffic into an in-trial sequence, properly spaced for handoff to the terminal area, would need to take place during en route descent from cruise altitude. With the present level of NAS Stage A automation and control procedures, and with present sector boundaries, it appears difficult to do. However, an automated

clearance planning and coordinating aid for merging descending arrivals might be devised to solve this problem. Such an aid would probably be an integral part of the en route metering function.

3. Shifting Traffic into the Higher Altitudes

This could produce sector workload imbalances, at least with the present sector boundaries. However, workload distribution problems should not be a permanent impediment to easing fuel-expensive altitude restrictions, especially if this workload is attributable mostly to transfers-of-control and radar monitoring. If the automation aids already cited are insufficient to prevent workload imbalances, sector re-design may be required.

CONCLUSIONS

1. Profile descent procedures and en route metering together offer the greatest fuel savings potential of any of the ideas considered. However that potential will be difficult to realize for all aircraft when arrival demand approaches runway capacity.

Profile descent procedures alone realize savings to the extent that they eliminate early descents into the lower altitudes to meet procedural altitude crossing restrictions and to provide level segments for terminal area speed control. However, to the extent that needed speed and vectoring control for metering and spacing in the terminal area is precluded by profile descent procedures, fuel can be lost, rather than saved, if runway throughput is lost during high demand periods.

Runway throughput can be lost by attempting to predict and absorb landing delays too far in advance of runway arrival. En route metering procedures can help sustain the fuel savings of profile descent procedures only if (1) the uncertain portion of the predicted delay is passed on to the terminal area for absorption if needed, and if (2) speed control, particularly during the en route descent phase of flight, is used to meter and space arrivals, in lieu of high altitude holding. Fuel-efficient speed control during descent implies that variable-gradient profile descent procedures should be used, permitting both reduced-thrust and idle-thrust descents to be conducted over a wide range of speeds and gradients.

2. Permitting cleaner, higher speed approaches to the runway offer significant fuel savings potential if computer-aided delayed-flap procedures are considered. The fuel savings of manual reduced-flap procedures are less significant, but do not require special airborne equipment. The problems of realizing these savings include (1) how to retain sufficient controllability in the terminal area for sequencing and spacing arrivals, (2) the impact on throughput of possibly having to place the last merge point on the final approach course farther from the runway to accommodate glide slope intercepts at higher altitudes, and (3) whether to permit mixing of aircraft equipped for delayed-flap approaches with those not equipped during periods of moderate-to-high demand for the runway. These problems must be solved if runway throughput is to be maximized, and landing delays minimized, when demand approaches runway capacity. Net fuel savings are quite sensitive to small losses in runway throughput.

3. Eliminating cruise or crossing altitude restrictions offers significant fuel savings potential wherever the difference between the desired and restricted altitude profile is large. In the

particular cruise altitude case studied, the per-flight saving is on the order of those found for profile descent procedures. The potential traffic conflicts that this particular restriction was designed to resolve were observed to occur infrequently enough to suggest time-sharing the desired altitudes, in lieu of segregation. The problems to be solved are (1) predicting occassional crossing conflicts between aircraft transitioning in altitude, and coordinating any necessary restrictions in real time, (2) handling merges with traffic heading for a common destination which would occur earlier and at higher altitudes, and (3) the potential for unbalancing controller workloads between sectors as currently structured.

4. Lowering the altitude restriction on the 250 knot speed limit in TCAs does not offer significant fuel savings for arrivals, given that profile descent procedures are implemented. The savings for departures are not large, assuming that uninterrupted climbs to altitudes above 10,000 feet are typical. Implementation raises safety issues, may require higher ceilings on TCAs, and would require a change in regulations.

5. Increasing the number of flight levels above FL290 offers fuel savings which are not large, given that other traffic is not a factor. Reducing the vertical separation to 1000 feet up to FL330 produces the greatest per-flight savings, but reducing to 1500 feet up to FL390 captures many more miles at cruise altitude and offers a slightly greater annual savings. Implementation raises safety and operational issues, and may require more accurate altimetry and pilotage. The FAA's Office of Systems Engineering and Management has proposed further investigation of some of these questions.

RECOMMENDATIONS

1. En route metering automation and delay absorption procedures should be developed to maximize ATC's ability to predict and absorb landing delays well before descent into the terminal area, using along-course speed reductions whenever practical. Advanced delay predictions should be reduced by the flying time uncertainties associated with them to avoid delaying aircraft unnecessarily. Credit for taking delays in advance must be given when forming the landing sequence. Fuel-efficient control of speed can be employed during the descent, if variable-gradient descent procedures are utilized. Sufficient speed and path controllability must be retained in the terminal area to absorb any residual delay, and to, establish the sequence and proper spacing along the final approach course.

2. Terminal area metering and spacing automation and procedures should be developed which can accommodate cleaner, higher speed approaches to the runway, whenever traffic demands permit. Since runway throughput can be lost with certain aircraft speed class or approach procedure mixes, the system should be designed to inhibit approach speed extremes when the demand is sufficiently high. The system should not permit runway throughput to be sacrificed under high demand levels, since small, perhaps imperceptible, losses in throughput can result in additional landing delays which negate the fuel savings.

3. Altitude clearance planning automation and control procedures should be developed to provide an alternative to the imposition of fixed cruise or crossing altitude restrictions. The automation should predict whether or not the desired cruise altitude or altitude profile is available as a function of traffic, and if not, what is the best available cruise or crossing altitude. The resolution of overtake situations between aircraft should also be provided for. If more than one sector is involved, clearance coordination should be automatically provided by the computer, with provision for controller override.

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FIGURES

1. INTRODUCTION

The cost of aviation jet fuel has essentially tripled from about 12¢ per gallon in 1972 to 35¢ per gallon in 1977. As a consequence, fuel consumption has become the dominant variable cost factor for many operators of civil turbojet aircraft, and fuel conservation has become a major cost-saving theme. Of the many fuel-saving ideas which have surfaced, the five we have chosen to look at would require significant changes in either the Federal Air Regulations or in the way the air traffic control system operates. The five ideas are:

1. Absorb landing delays before leaving en route airspace.

2. Permit cleaner, higher speed approach and landing procedures.

3. Lower the altitude restriction on the 250 knot speed limit in TCAs.

4. Increase the number of flight levels above 29,000 feet.

5. Eliminate fixed cruise or crossing altitude restrictions.

Of these, all but number 4 involve finding more fuel-conservative solutions to the aircraft separation and traffic flow problems associated with turbojet operations to and from busy terminal areas. Number 4 relates to the structuring and capacity of en route airspace. This study has three objectives:

1. Generate comparative estimates of the fuel-saving potential of each of these ideas, both on a per-flight basis and on a national annual average basis.

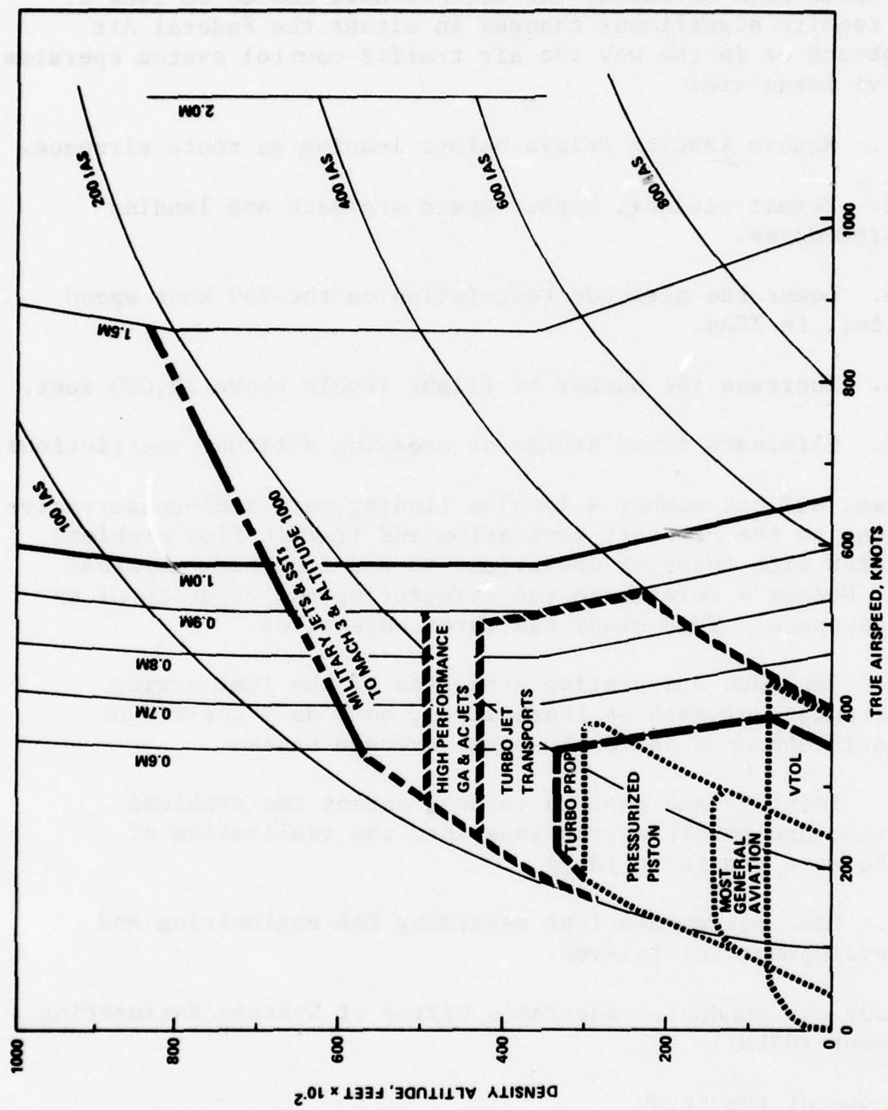
2. Identify and explore to some extent the problems with, and possible solutions for, the realization of the more promising ideas.

3. Make recommendations regarding FAA engineering and development initiatives.

The study was conducted for FAA's Office of Systems Engineering Management (OSEM).

1.1 Scope of the Study

The study addressed civil turbojet transport operations (includes turbofans). As illustrated in Figure 1-1, the turbojet transport



SOURCE: REFERENCE 1-1

FIGURE 1-1
SPEED AND ALTITUDE RANGES OF AIRCRAFT CLASSES

can be characterized as an aircraft which today typically cruises between 18,000 and 43,000 feet and at speeds below 0.9 Mach. According to Reference 1-2, the estimated fuel consumed by U.S. domestic civil aviation during FY76 was:

	Billions of Gallons, FY76		
	Jet Fuel	Aviation Gasoline	Total
Air Carrier	7.8	0	7.8 (88%)
General Aviation	0.6	0.5	1.1 (12%)
			8.9 (100%)

Thus, air carrier turbojet transports account for about 9 out of every 10 gallons of aviation fuel consumed by U.S. civil aviation. In addition, about half of the remaining gallons are consumed in a similar-performing business jet aircraft. Clearly, this class of aircraft is the most important when considering ways of better accommodating fuel-efficient aircraft operations within the ATC system.

The five ideas addressed by this study all concern ways of allowing turbojets to operate closer to fuel-optimal speed schedules and altitude profiles, while at the same time assuring that traffic separation can be maintained, excessive flight delays are not incurred, and that controller workload is not significantly increased.

While many of the lessons learned in studying civil turbojet transport operations will certainly carry over to military operations in similar aircraft, the subject of fuel conservation in military aircraft is beyond the scope of this study.

Figure 1-1 also serves as a reminder that the subject could be extended to all popular aircraft types which operate in the ATC system. The lessons learned in studying turbojet aircraft may or may not apply to turboprop and piston aircraft.

2. ABSORB LANDING DELAYS BEFORE LEAVING EN ROUTE AIRSPACE

"Profile descent" and "en route metering" procedures are being developed and implemented by the FAA to "...reduce flying time at altitudes below 10,000 feet (above airport elevation)..." in the interests of conserving turbojet fuel and reducing aircraft exposures to other traffic operating at the lower altitudes (Reference 2-1).

Before the concepts of "profile descents" and "en route metering" were introduced, aircraft would arrive randomly at the periphery of the terminal area, and the tasks of metering, sequencing, and spacing those arrivals to the runway were performed by terminal area controllers. In periods of moderate to high traffic demand, the aircraft would typically enter the terminal area level at low altitudes, go through a few speed reductions during step-down descents, before being vectored onto the final approach course These speed reductions and vectors provided ATC with the control capability to absorb the normal landing delays required by the sequencing and spacing process. Any metering delay which was outside the controllability range of terminal area speed or path control was typically absorbed in a low altitude holding pattern.

Profile descent procedures are designed to allow the pilot to execute an uninterrupted descent from cruise altitude to the runway in a fuel-conservative manner. When such descents are made in clean configuration and at near-idle thrust, the potential energy of the aircraft at altitude can be converted into a large share of the kinetic energy needed to reach the runway, thus conserving fuel. Whether the pilot will be able in fact to complete such a descent is currently a function of traffic demand for the runway and the skills of the air traffic controller. Section 2.1 evaluates the fuel-savings potential of profile descent procedures when competition for the use of the runway is not a factor.

When competition for the use of the runway is a factor, en route metering procedures are to be used to absorb landing delays at altitudes above 10,000 feet. These procedures establish desired spacing criteria between the aircraft arriving via the several feeder fixes to the terminal area. For example, itinerant high altitude arrivals to Atlanta's Hartsfield Airport are spaced in distance (e.g., 10 miles in-trial) to meet the acceptance rate established for each feeder fix. Alternatively, such arrivals to Denver's Stapleton Airport are tentatively scheduled to the runway using a nominal time spacing. The nominal flying time from the feeder fix to the runway is then accounted for, resulting in a desired feeder fix crossing time for each metered arrival.

(The basic difference between these two methods is that the Denver scheme attempts to synchronize the several flows to the runway, while the Atlanta scheme does not.)

In either case, the difference between when the aircraft would cross the feeder fix without further ATC intervention, and when they should cross, constitutes a predicted landing delay which is to be absorbed before each aircraft crosses the feeder fix and begins its profile descent. Section 2.2 addresses the sensitivity of profile descent fuel savings to possible losses in runway throughput. Such losses can easily occur if the en route metering process delays some aircraft unnecessarily due to uncertainties in predicting the amount of landing delay needed before the aircraft leaves en route airspace. These same uncertainties may also cause aircraft to arrive in the terminal area too soon, suggesting that some terminal area speed control and vectoring capabilities should be retained.

One important way to conserve jet fuel would be to anticipate landing delays far enough in advance to permit the delayed aircraft to slow down while en route to the airport, rather than adding additional miles of flight in a holding stack after the route miles have been covered. The logic for such a strategy is outlined in Section 2.3 and is shown to provide both significant delay absorption and fuel-saving potential, especially if both idle thrust and reduced thrust descent profiles and speeds are incorporated. Of course, such prediction of landing delays well in advance would have to be discounted appropriately to avoid the fuel penalties identified in Section 2.2.

Section 2.4 puts the topics of this chapter into perspective by considering the fuel consumption and arrival time controllability characteristics of the B727-200 series aircraft as a function of altitude. It is shown that it is more important for fuel conservation not to delay an airborne aircraft unnecessarily at any altitude, than it is to avoid holding or vectoring it, when needed, at low altitudes within the terminal area.

2.1 Potential Fuel Savings and Controllability of Profile Descent Procedures on a Single Flight Basis

As an example, Figure 2-1 shows the old step-down procedure from the Lyons arrival fix to Denver's Stapleton Airport. Normally the aircraft would be cleared to descend from cruise altitude (in this case 35,000 feet MSL) in time to meet an altitude crossing restriction of 12,000 feet MSL at the Lyons intersection. The aircraft would level out and be subjected to a couple of speed reductions before continuing the descent to runway 26L.

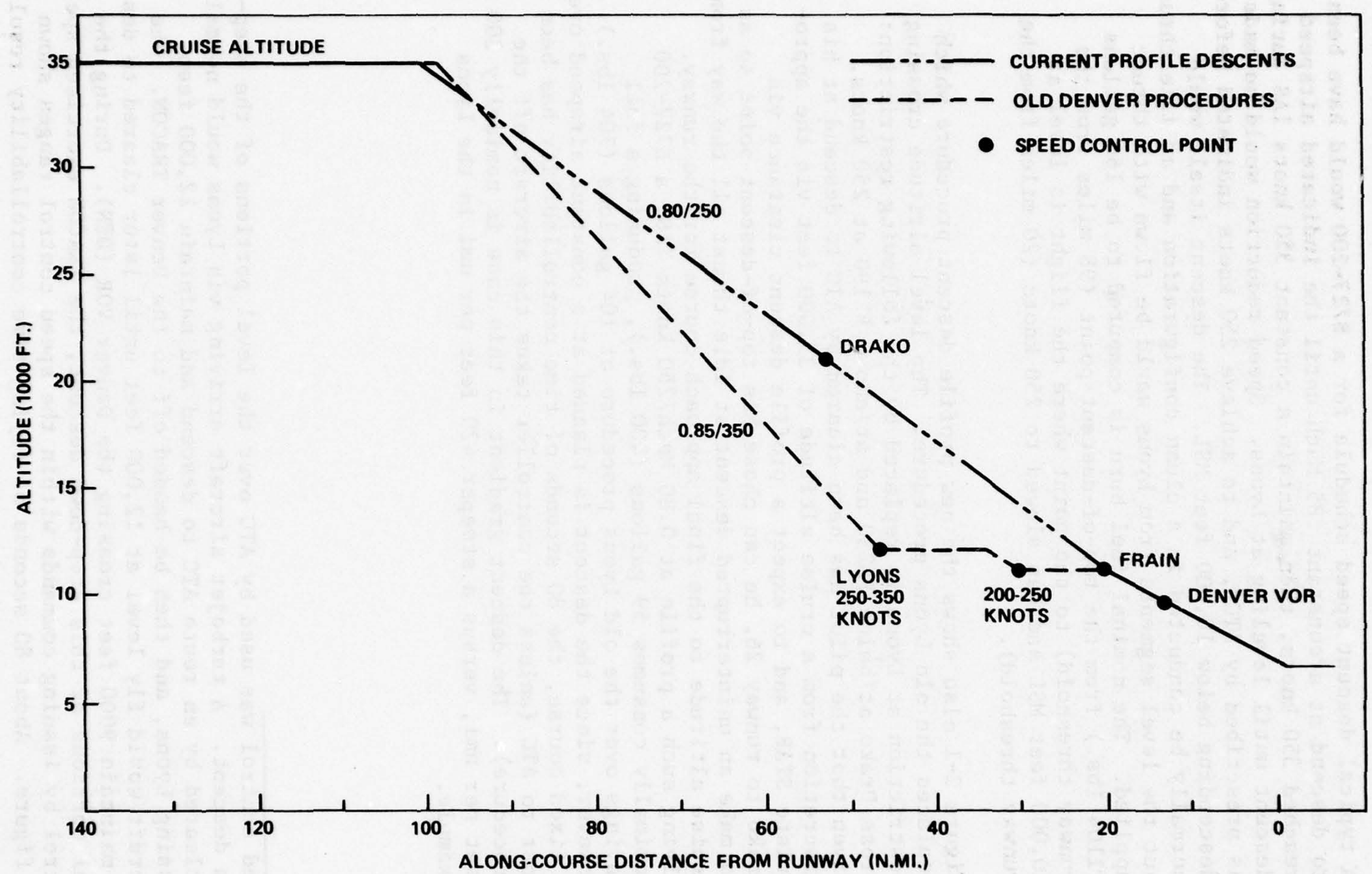


FIGURE 2-1
STEP-DOWN VERSUS CURRENT PROFILE DESCENT PROCEDURES

A typical descent speed schedule for a B727-200 would have been to descend at a constant .85 Mach until the indicated airspeed reached 350 knots, then maintain a constant 350 knots IAS during descent until leveling at Lyons. Speed reduction would be made as prescribed by ATC*, and to achieve 250 knots indicated before descending below 10,000 feet MSL. The descent itself would normally be conducted in a clean configuration and at idle thrust, but the level segments from Lyons would be flown with thrust applied. The nominal fuel burn is computed to be 160 gallons (1104 lbs.) from the top-of-descent point (98 miles from the runway threshold) to the point where the flight is level at 10,000 feet MSL and has slowed to 250 knots (20 miles from the runway threshold).

Figure 2-1 also shows the new profile descent procedure which replaces the old Lyons procedure. The level altitude crossing restriction at Lyons is replaced by the following restriction: cross Drako at/below FL230 and at/above FL190 at 250 knots. Given that the pilot has been cleared by ATC to descend at his discretion from a cruise altitude of 35,000 feet via the appropriate STAR, and to expect a profile descent clearance via Drako to runway 26, he can chose his top-of-descent point so as to make an uninterrupted descent at idle thrust all the way from cruise altitude to the final approach course for the runway. Flying such a profile at 0.80 Mach/250 knots IAS, a B727-200 nominally consumes 59 gallons (400 lbs.), producing a fuel savings over the old Lyons procedure of 104 gallons (704 lbs.). However, since the descent is planned at a constant airspeed over a fixed course, the 80 seconds of time controllability has been lost to ATC (unless the controller takes the aircraft off the procedure). The descent gradient in this case is nominally 300 feet per nmi, versus a steeper 420 feet per nmi in the Lyons example.

---

* Speed control was used by ATC over the level portions of the step-down descent. A turbojet aircraft arriving via Lyons would normally be cleared by en route ATC to descend and maintain 12,000 feet crossing Lyons, and then be handed off to the Denver TRACON. The aircraft would fly level at 12,000 feet until later cleared to descend and maintain 9000 feet crossing the Denver VOR (DEN). During the level portions of this step-down descent, the TRACON exercised speed control by issuing commands within the speed control ranges shown in the figure. About 80 seconds of flying time controllability result.

2.2 The Sensitivity of Fuel Savings to Possible Losses in Runway Throughput

It has been shown that uninterrupted descents at idle power, when compared to the old step-down procedures, could save about 704 lbs of fuel on a single flight basis. However, when there is competition for the use of the runway, landing delays will have to be absorbed prior to starting the profile descent, if low altitude holding is to be avoided and low altitude vectoring is to be minimized. This requires that the serving en route ATC facility meter arrivals into the terminal area based on predicted airport acceptance rate and landing sequences, required spacings, and nominal flying times from the metering fix to the runway. In theory at least, this prediction process will be subject to the normal errors of forecasting (all landing aircraft may not have been accounted for, errors in flying time estimates due to prevailing winds, etc.). The delay absorption process will also be subject to errors (the delay actually taken will not always equal the predicted delay required).

The question arises: What effect might these delay prediction and absorption errors have on system or aircraft performance, relative to net savings? In this section, an analytical argument is developed which shows that they can have a significant impact (loss) on relative runway throughput, during moderate-to-heavy demand periods. This loss is relative to the throughput previously obtained when the TRACON was at liberty to absorb any landing delays when the aircraft were much closer to the runway and all landing aircraft could be accounted for.

In discussing en route metering and profile descents with regard to fuel consumption, two basic factors should be kept in mind.

1. According to schemes currently being considered to implement FAA Order No. 7110.72, decisions by the en route system are made at least 36 flying miles (about 10 minutes) before runway threshold time. Previous error analysis work has indicated that an error of about one second per nmi can be expected in the prediction of flying time to the threshold. Therefore, assuming the analysis is correct, uninterrupted profile descents are feasible only up to a point, and at some low altitude, the terminal controller must exercise spacing control by vectoring or speed control in order to maintain separation at the merge points and at the runway. A possible scenario is depicted in Figure 2-2.

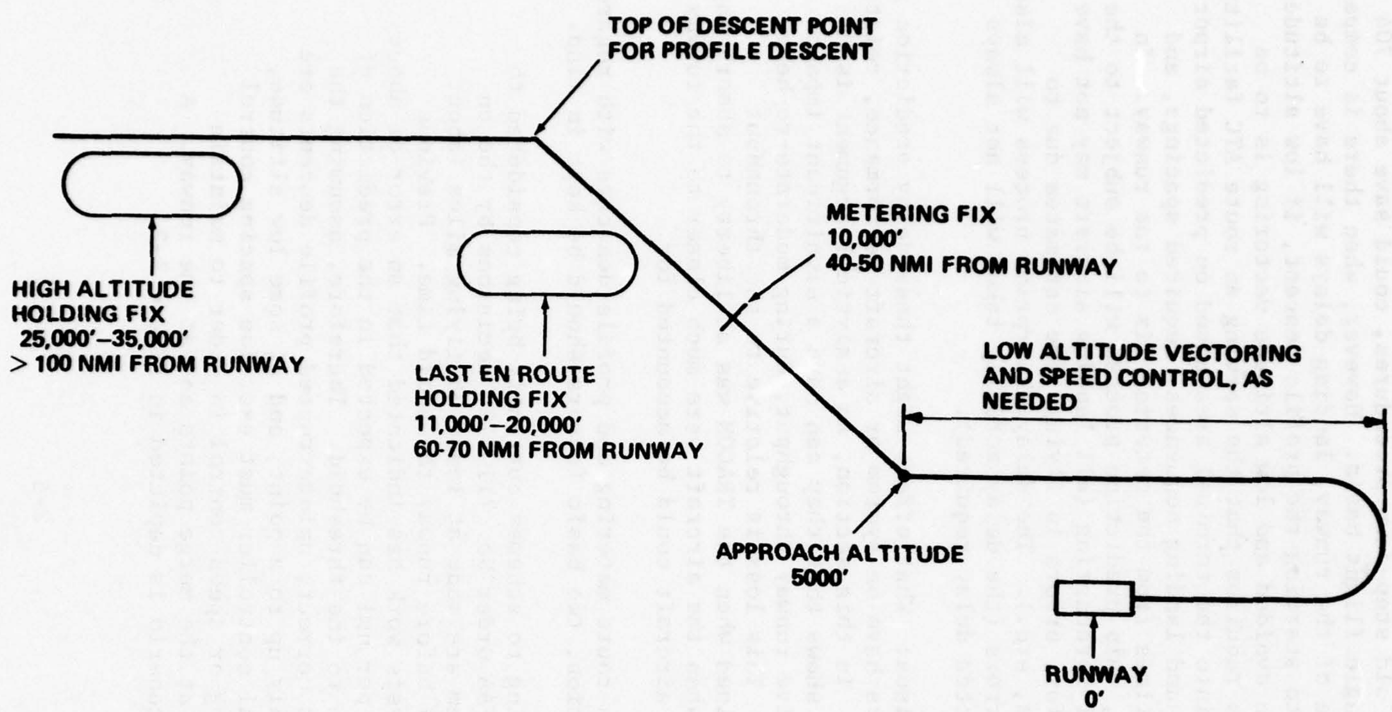


FIGURE 2-2
EN ROUTE METERING AND USE OF PROFILE
DESCENTS ILLUSTRATED

2. The terminal area's procedures must be such that the resulting variations in spacing do not result in loss of runway throughput. Simulation and analysis has shown that small reductions in airport runway throughput (13%) can result in arrival aircraft delays which result in fuel consumptions larger than the benefits of profile descents. That is, it is important that the use of profile descents do not create even a small, perhaps imperceptible, loss in runway throughput. Figures 2-3 and 2-4 illustrate this point. Figure 2-3 presents the time delays which will be introduced due to a given loss in arrival runway throughput, as a function of arrival traffic demand.* From Figure 2-3 we see that if a runway can normally land 35 aircraft per hour, but, for whatever reason, operates as a runway only capable of landing 1, 2, 3, 4 or 5 less than that in an hour, the average additional delays introduced are significant, whenever traffic demands are more than 30 aircraft per hour.**

Figure 2-4 shows that at a full demand, a loss of as little as 13% of arrival runway throughput*** can result in a loss of all the fuel benefits due to use of profile descents (assumed here to be the 704 lbs. per aircraft computed in previous section).

---

* Arrival runway throughput refers to the number of aircraft which can be landed per unit time (in an hour). Projected throughput is dependent upon having both a demand for the runway and knowing the inter-arrival spacings which are permitted or are achievable at some measuring point along the final approach course (e.g., at the runway threshold). In the absence of a specified demand, a saturating mix of aircraft can be assumed. In this case, arrival throughput is equal to the runway's capacity for accepting arrivals only (see Reference 3-11 for the definition of runway capacity).

** See the brief description of the landing delay model used in Appendix A.1.

*** The loss in throughput being referred to here is for the aircraft involved in the profile descents. That is, if runway throughput is kept up by inserting local arrivals into the traffic gaps, the fuel benefit of the profile descents is still lost to the aircraft using them.

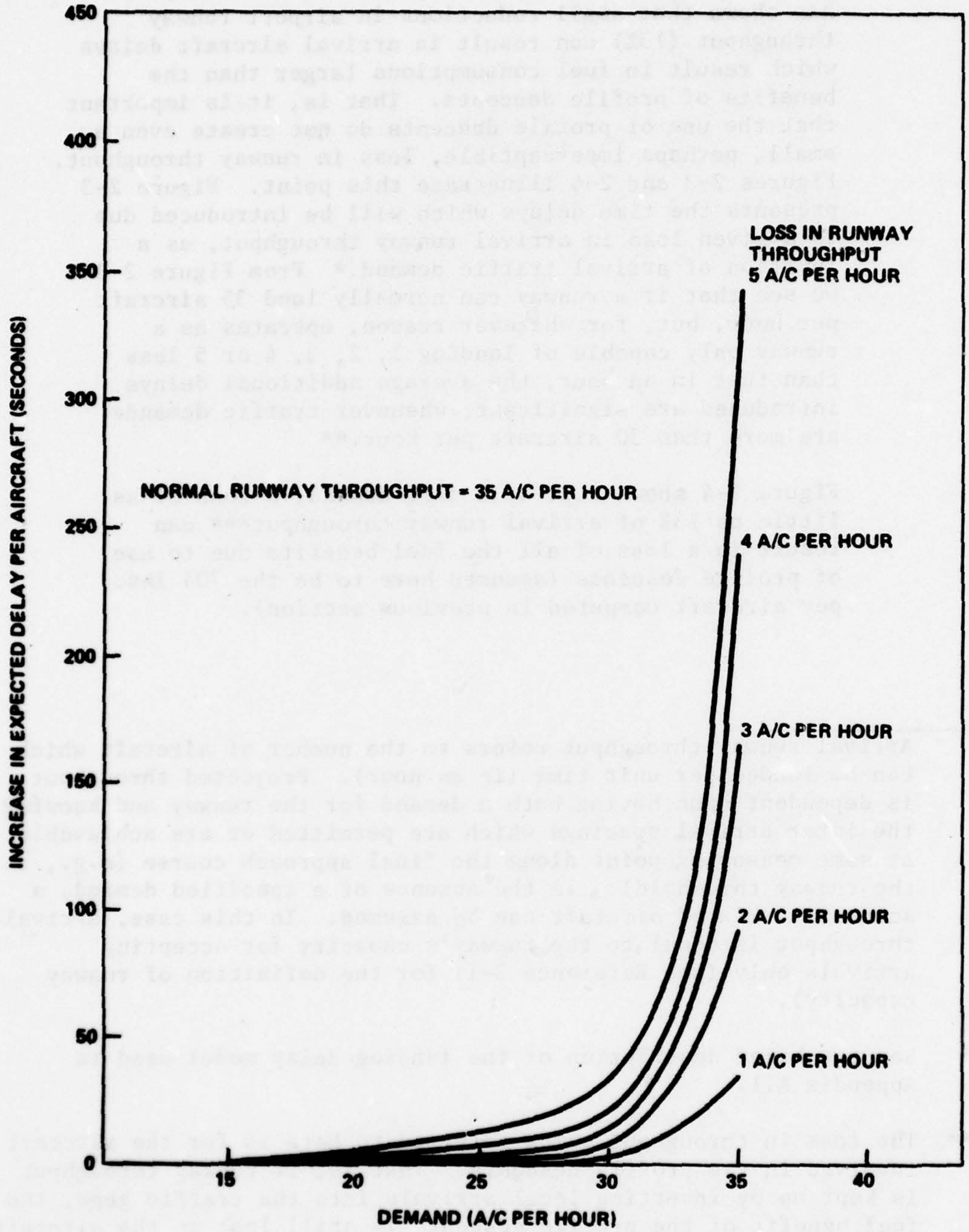


FIGURE 2-3
INCREASE IN TIME DELAY (ABOVE AVERAGE DELAYS) DUE TO A LOSS IN RUNWAY THROUGHPUT AS A FUNCTION OF DEMAND (FOR ARRIVALS ONLY)

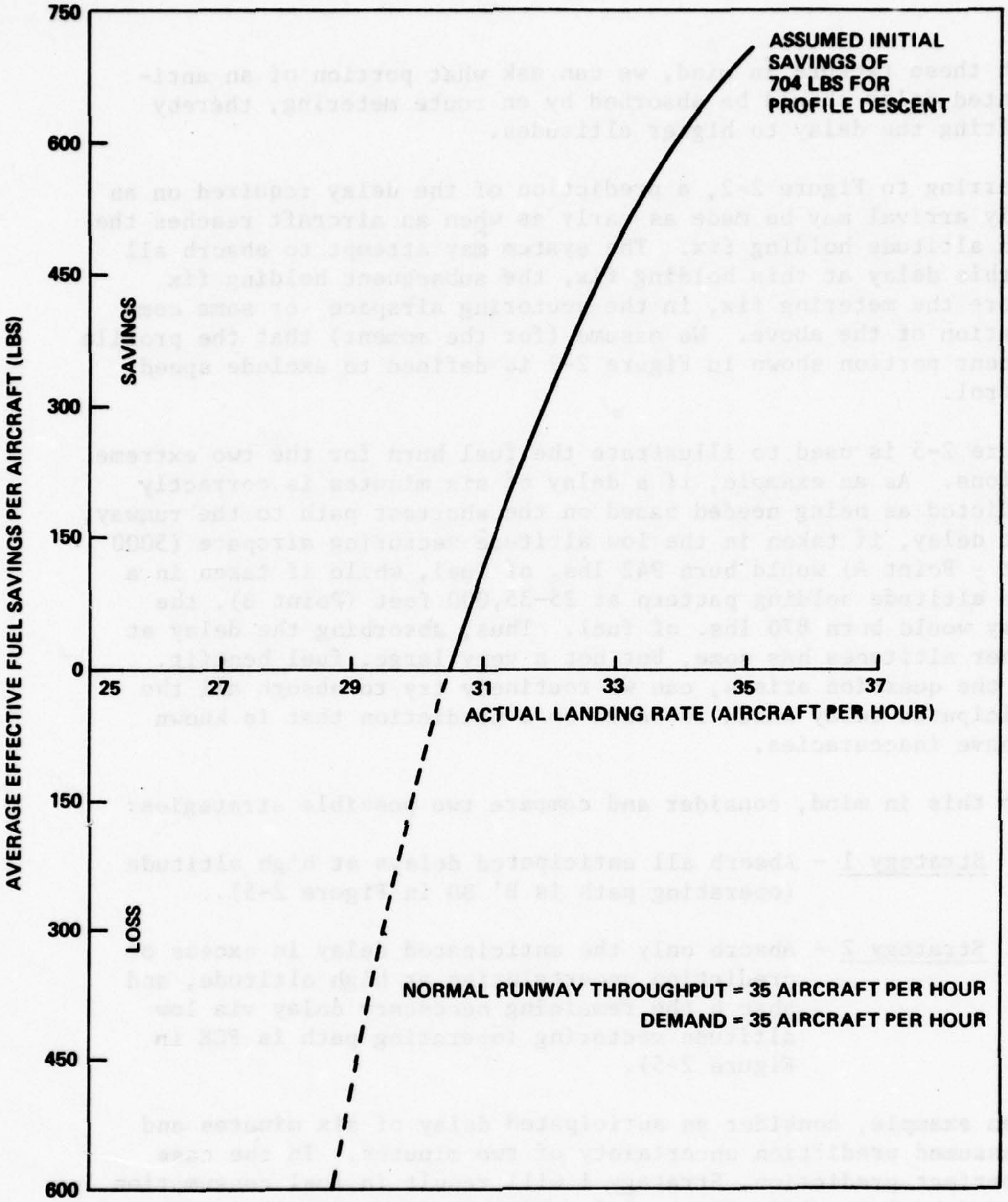


FIGURE 2-4
EFFECTIVE FUEL SAVINGS AS A FUNCTION OF ACTUAL RUNWAY THROUGHPUT
(FOR ARRIVALS ONLY)

With these factors in mind, we can ask what portion of an anticipated delay should be absorbed by en route metering, thereby shifting the delay to higher altitudes.

Referring to Figure 2-2, a prediction of the delay required on an early arrival may be made as early as when an aircraft reaches the high altitude holding fix. The system may attempt to absorb all of this delay at this holding fix, the subsequent holding fix before the metering fix, in the vectoring airspace, or some combination of the above. We assume (for the moment) that the profile descent portion shown in Figure 2-2 is defined to exclude speed control.

Figure 2-5 is used to illustrate the fuel burn for the two extreme options. As an example, if a delay of six minutes is correctly predicted as being needed based on the shortest path to the runway, that delay, if taken in the low altitude vectoring airspace (5000 feet - Point A) would burn 942 lbs. of fuel, while if taken in a high altitude holding pattern at 25-35,000 feet (Point B), the delay would burn 870 lbs. of fuel. Thus, absorbing the delay at higher altitudes has some, but not a very large, fuel benefit. Now the question arises, can we routinely try to absorb all the anticipated delay which is based on a prediction that is known to have inaccuracies.

With this in mind, consider and compare two possible strategies:

<u>Strategy 1</u> - Absorb all anticipated delays at high altitude (operating path is B' BD in Figure 2-5).

<u>Strategy 2</u> - Absorb only the anticipated delay in excess of prediction uncertainties at high altitude, and absorb the remaining necessary delay via low altitude vectoring (operating path is FCE in Figure 2-5).

As an example, consider an anticipated delay of six minutes and an assumed prediction uncertainty of two minutes. In the case of perfect prediction, Strategy 1 will result in fuel consumption denoted by Point B in Figure 2-5, while Strategy 2 will result in fuel consumption denoted by Point C. The difference between fuel burn at B and C is about 30 lbs.

<u>Early Arrival</u>

In the case of a two minute prediction error in the direction which results in the aircraft arriving earlier than expected in the low altitude airspace, both Strategy 1 and 2 result in the need for an added two minutes of low altitude vectoring. Thus,

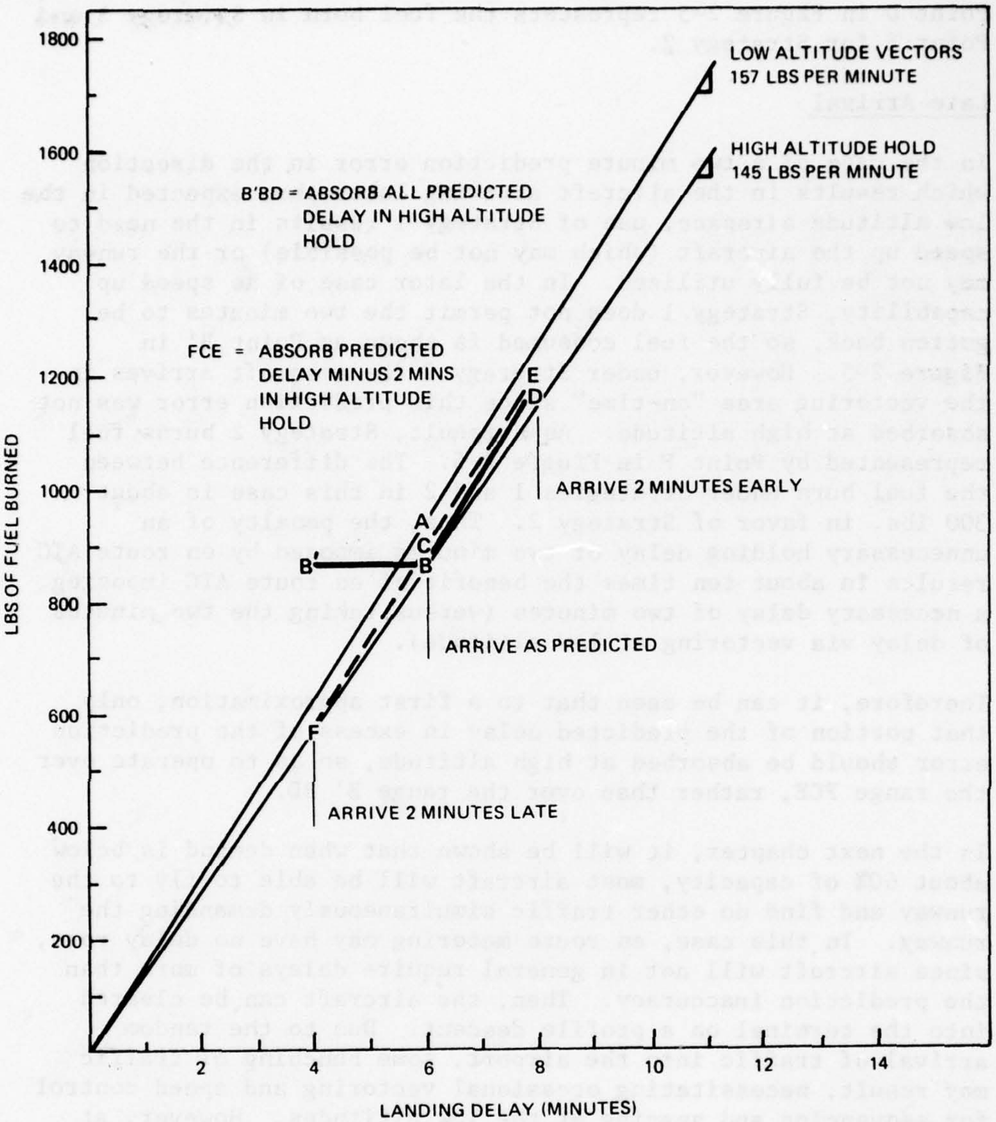


FIGURE 2-5
COMPARISON OF EN ROUTE METERING STRATEGIES
(FOR A B727-200 AT 160,000 LBS, ISA)

the fuel burn difference between the strategies remains at 30 lbs. Point D in Figure 2-5 represents the fuel burn in Strategy 1 and Point E for Strategy 2.

Late Arrival

In the case of a two minute prediction error in the direction which results in the aircraft arriving later than expected in the low altitude airspace, use of Strategy 1 results in the need to speed up the aircraft (which may not be possible) or the runway may not be fully utilized. In the later case of no speed up capability, Strategy 1 does not permit the two minutes to be gotten back, so the fuel consumed is shown as Point B' in Figure 2-5. However, under Strategy 2 the aircraft arrives in the vectoring area "on-time" since this prediction error was not absorbed at high altitude. As a result, Strategy 2 burns fuel represented by Point F in Fiugre 2-5. The difference between the fuel burn under Strategies 1 and 2 in this case is about 300 lbs. in favor of Strategy 2. Thus, the penalty of an unnecessary holding delay of two minutes imposed by en route ATC results in about ten times the benefit of en route ATC imposing a necessary delay of two minutes (versus taking the two minutes of delay via vectoring at low altitude).

Therefore, it can be seen that to a first approximation, only that portion of the predicted delay in excess of the prediction error should be absorbed at high altitude, so as to operate over the range FCE, rather than over the range B' BD.

In the next chapter, it will be shown that when demand is below about 60% of capacity, most aircraft will be able to fly to the runway and find no other traffic simultaneously demanding the runway. In this case, en route metering may have no delay role, since aircraft will not in general require delays of more than the prediction inaccuracy. Then, the aircraft can be cleared into the terminal on a profile descent. Due to the random arrival of traffic into the airport, some bunching of traffic may result, necessitating occasional vectoring and speed control for sequencing and spacing at the low altitudes. However, at low traffic demands the probability that most aircraft will be permitted to fly an uninterrupted profile descent, from cruise altitude to the final approach course (i.e., no vectoring or speed control) is very high.

As traffic builds up above the 60% of capacity point, aircraft will require delays due to other traffic competing for the runway. As traffic approaches or exceeds full runway capacity, delays will become larger than the prediction accuracy and en route metering will begin to do its delay shifting (to only

include the predicted delay over and above the delay prediction inaccuracy). Subsequently, the aircraft can be issued a profile descent down to low altitude. At low altitude, the terminal area will have to use vectoring and speed control to accomplish final sequencing and spacing (due to the random factors which impact prediction inaccuracy which originally were ignored by the en route system) so that runway utilization is not reduced. As a consequence, under profile descent operations with en route metering, the pilot will see low altitude terminal area vectoring as being somewhat similar to today's operation - i.e., delaying vectors will be rare under light traffic and frequent under heavy traffic conditions. Under the new operation, the duration of delaying vectors will be shorter since part of the necessary delay is absorbed at high altitude.

It is shown in the previous section that when fixed-gradient profile descents are made into the terminal airspace, not only is all speed control capacity lost, but also the aircraft accumulate larger flying time deviations due to flying uncontrolled longer distances. At airports where vectoring airspace exists near the final approach course (e.g., airspace to permit an extended downwind), the loss of speed control during the profile descent does not appear to present a big problem. However, at airports with little vectoring airspace, where speed control is the major spacing tool, this could create significant problems to the controller and his ability to maintain high runway throughput. In the latter case, the use of profiledescents in the terminal may have to be limited to low traffic periods (due to the relationships between runway throughput and fuel consumption discussed previously). Alternatively, speed control during descent through variable-gradient procedures could be introduced (See Section 2.3).

Even if the accuracy of the prediction of flying time to the runway is significantly improved, there are other factors that prevent the en route system from accurately predicting the aircraft's likely landing time. These include the inability to predict the exact landing sequence and the occurrence of specific events such as the terminal area's need to accommodate local VFR arrivals, missed approaches, departures, specific runway occupancy times of aircraft, etc. Also, the spacing achieved in visual meterological conditions are partly dependent upon pilotage, since ATC does not maintain the separation once the aircraft is cleared for a visual approach to the runway. Therefore, the en route metering function can use predicted landing times only as a means of ordering the traffic flowing into the terminal system, but not to exactly sequence and schedule runway threshold crossings.

The reliability of en route decisions will partly depend upon the information available from the terminal airspace. Accordingly,

the en route metering and the terminal spacing function probably have to function with a close interface for effective operation. Further, it is to be expected that en route metering will be most effective under instrument meterological conditions (violent weather excluded) and for arrival-only runways, since the sequence and spacings will then be the most predictable.

2.3 Recovering Lost Speed Controllability While Saving Fuel Using Variable-Gradient Profile Descents

As shown in the previous section, controllability must be retained if runway throughput is not to be sacrificed during periods of runway demand. However, it is not necessary for ATC to lose speed control during en route descents at idle thrust if a range of descent gradients can be tolerated. For example, a pilot descending at 250 knots indicated can drop the nose of the aircraft, gravity accelerate to a new desired IAS, and raise the nose again to stabilize at the new descent speed and gradient.

The following sections address conceptually the use of idle thrust and partial-thrust descent procedures as a means of regaining speed control for metering and spacing purposes. Either en route or terminal area control of the descent speed anywhere from cruise altitude to the terminal vectoring area is contemplated. The assumption is that automated logic could be developed to aid the controller in deciding whether, when, and how much of a speed reduction could be used to maintain separation, or to absorb a predicted landing delay. Figure 2-6 illustrates a family of such descent procedures for a B727-200.

2.3.1 Speed Controllability and Average Fuel Savings of Variable-Gradient Descents

Table 2-1 shows that if variable speed/gradient idle descent profiles, with speeds ranging from 250 to 390 knots, are permitted in the en route airspace along with the present profile descent procedures starting at Drako, a controllability of 82 seconds can be recovered with an average savings of 637 lbs of fuel per flight. These fuel savings have been computed by taking the average of the savings when the aircraft fly over the shallowest and the steepest gradients.

It is important to note that, even though one may observe a small loss in savings (from 704 lbs/flight to 637 lbs/flight) by using variable-gradients as compared to rigid descent profiles, the savings with the variable-gradients approach represent an average and could be achieved by all flights under medium/high density traffic, whereas, only a few aircraft would be able to use rigid profiles under heavy traffic demands to realize the larger fuel

TABLE 2-1

PERFORMANCE COMPARISON FOR VARIABLE-GRADIENT SPEED CONTROL USING IDLE DESCENTS ONLY*

	OLD DENVER DESCENTS PROCEDURE OVER LYONS	CURRENT PROFILE DESCENTS FROM DRAKO	VARIABLE-GRADIENT SPEED CONTROL BEGINS***	
			FROM DRAKO AT 21,000 FT	FROM TOP OF DESCENT AT 35,000 FT
SPEED CONTROLLABILITY, SECONDS	80	0	82	212
AVERAGE FUEL CONSUMPTION, LBS	1104	400**	467	569
AVERAGE FUEL SAVINGS LBS (GALS)	0 (REFERENCE)	704 (104)	637 (94)	535 (79)

* BASED ON B727-200 (145,000 LBS) DATA OVER 80 NMI. FLYING DISTANCE FROM CRUISE ALTITUDE OF 35,000 TO FINAL ALTITUDE OF 11,000 FEET.

** ASSUMES CONTINUOUS DESCENT FROM CRUISE ALTITUDE AT 250 KNOT IAS INTO TERMINAL AREA.

*** DRAKO IS THE TRANSFER-OF-CONTROL FIX BETWEEN THE ARTCC AND TRACON. "FROM DRAKO" SUGGESTS THAT ONLY THE TRACON CAN EXERCISE VARIABLE-GRADIENT SPEED CONTROL. " FROM TOP-OF DESCENT" SUGGESTS THAT THE ARTCC CAN EXERCISE SUCH CONTROL WITH RESPECT TO A METERING FIX AT THE 11,000 FT & 250 KNOT POINT.

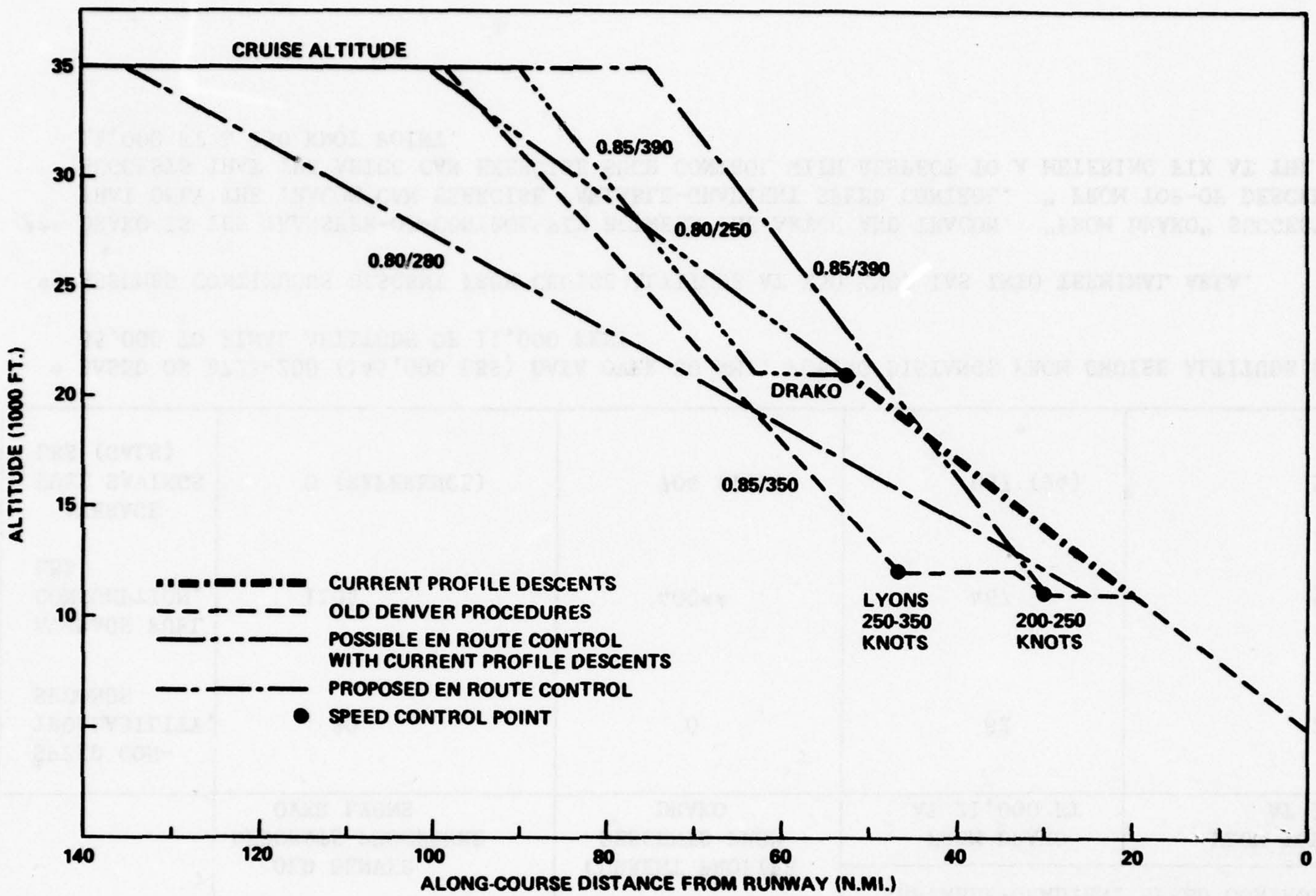


FIGURE 2-6
VARIABLE-GRADIENT PROFILE DESCENT PROCEDURES

savings. As such, variable-gradient procedures may provide larger overall savings than the present profile descent procedures.

In cases where the variable-gradient descents can start from cruise altitudes, 212 seconds of controllability can be achieved with an average fuel savings of 535 lbs/flight.

Since the aircraft require more fuel during cruise than in descent with partial power, it can be even more fuel-economical to let aircraft descend on very shallow gradients using partial thrust, airspace permitting. Such partial-thrust descents would provide additional savings in fuel, compared to flying longer cruise distances and then descending at idle power. Table 2-2 shows a relative comparison of controllability and fuel savings using partial-thrust descent procedures and idle-thrust procedures for aircraft flying a distance of 135 nmi between 35,000 feet and 11,000 feet (Figure 2-1). It can be seen that average savings in fuel increased from 535 lbs. to 904 lbs. for a similar set of variable-gradient procedures.

2.3.2 Outline of a Logic for Fuel-Efficient En Route Metering Strategy Using Speed Control

In cases where the en route metering system assumes control of the aircraft farther out from the runway, in addition to the use of fuel economic descent profiles, the control strategy now outlined determines optimum speed reductions, based on the aircraft's Long Range Cruise (LRC) or the maximum endurance speed, to absorb given ATC delays. As a first step, the strategy ascertains whether the desired en route delay can be absorbed solely through an appropriate choice of speed/gradient profile. This is possible when the desired delay is less than the control capability achievable through the variable-gradients shown in Table 2-2. If the desired delay is larger than the controllability available through variable-graidents, then the logic would attempt to get control through speed change in cruise as described in the following paragraphs.

An aircraft requires minimum fuel per unit distance when it cruises at its LRC speed. Hence, in order to absorb delay through a speed change, a speed reduction from a current higher cruise speed to the aircraft's LRC speed would be the most fuel-efficient.

To estimate an aircraft's LRC speed, it would be necessary to know or to estimate its weight. Given a weight estimate, its assigned altitude, and the type of aircraft, an LRC estimate can be computed. For the distances over which such metering control is likely to be imposed (within one center's boundary), the LRC speed can be treated as a constant.

TABLE 2-2

PERFORMANCE COMPARISON FOR VARIABLE-GRADIENT SPEED CONTROL USING IDLE-THRUST OR REDUCED-THRUST DESCENTS*

	OLD DENVER PROCEDURE OVER LYONS	CURRENT PROFILE DESCENTS OVER DRAKO	VARIABLE-GRADIENT SPEED CONTROL BEGINS		
			AT DRAKO (FROM 21,000 FT)	AT IDLE-THRUST TOP-OF-DESCENT (FROM 35,000 FT)	AT REDUCED-THRUST** TOP-OF-DESCENT (FROM 35,000 FT)
SPEED CONTROLLABILITY, SECONDS	80	0	98	228	306
AVERAGE FUEL CONSUMPTION, LBS	1752	1015***	1100	1164	848
AVERAGE FUEL SAVINGS LBS (GALS)	0 (REFERENCE)	737 (108)	652 (96)	588 (86)	904 (133)

* BASED ON B727-200 (145,000 LBS) DATA OVER 115 NMI. FLYING DISTANCE FROM CRUISE ALTITUDE OF 35,000 FT TO FINAL ALTITUDE OF 11,000 FT AND INITIAL CRUISE SPEED OF 0.85 MACH.

** FIFTY-FIVE PERCENT N1 CLEAN AND 0.80/250 KNOTS.

*** ASSUME CRUISE AT 0.80 AND CONTINUOUS DESCENT FROM CRUISE ALTITUDE AT 250 KNOTS IAS INTO TERMINAL AREA.

Once an aircraft's LRC speed is estimated, the available speed control, if any, can be computed. For a aircraft cruising at speed higher than its LRC speed, the controllability is the difference between the flying times at an aircraft's filed cruise speed and its LRC over the available cruise distance (i.e., distance between the aircraft's current position and the planned top-of-descent point). The planned top-of-descent point which terminates the cruise segment would depend upon the selected speed/gradient profile.

The next step in the control process is to determine the speed control available to the top-of-descent point for an ATC assumed nominal speed/gradient profile or a descent profile based on pilot's discretion. If the desired delay is within the speed controllability, the control strategy determines the location along the route to issue an LRC speed command on the aircraft with the nominal or pilot discretionary descent clearance.

When the desired delay is more than the above mentioned controllability, speed control is determined by assuming lowest speed/shallowest gradient descent profile. This implies that the speed control is not only being achieved through reduction to LRC, but also a total control through variable-gradient descent profiles. If the desired delay is less than the composite speed control, the control logic would determine the location (before top-of-descent point for the slowest descent) to issue LRC command to the aircraft, and also would plan on issuing a clearance for the slowest descent gradient.

For the cases where the desired delay exceeds the control achieved through procedures described above, the ATC system would have to hold the aircraft (assuming no vectoring is available). In these situations, the aircraft are simply required to burn fuel to absord delay without regard to fuel mileage considerations. Rather than requiring an aircraft to orbit at a holding fix, it may be worthwhile to let the aircraft fly at its maximum endurance speed over a portion of the available cruise distance, if this would compensate for the desired delay. Hence, before deciding to hold the aircraft, the strategy determines the speed control through reduction to the aircraft's maximum endurance speed plus total control through variable-gradient descents. If the ATC desired delay is within this controllability, the location to issue maximum endurance speed command would be generated by the control logic in conjunction with a clearance to descend at the slowest speed. This procedure would not only avoid orbital holding, which requires extra pilot maneuvers than straight flying, but also, would minimize the large time deviations possible when an aircraft breaks off from the holding pattern.

2.4 The Relationships Between Fuel Consumption and Speed Controllability as a Function of Altitude for Different Speed Schedules

The purpose of this section is to explain in another way the results of the preceeding sections and to graphically illustrate some relationships which are important to the subject of fuel-efficient delay absorption. The curves presented were derived for a B727-200 from Reference 6-3, using ISA data (no wind), and an average weight of 160,000 lbs. The results are generally true for other weights and turbojet transport types, except for scaling factors.

2.4.1 Fuel Consumption as a Function of Altitude and Speed Schedule

Figure 2-7 illustrates that fuel consumption per unit distance in a turbojet aircraft is definitely minimized at some particular high altitude (in this case, about 33,000 feet), and that the Long Range Cruise (LRC) speed schedule is the one which minimizes fuel consumption per mile regardless of altitude. The fuel penalties in cruising at non-optimum altitudes are investigated further in Chapters 5 and 6.

Figure 2-8 illustrates that while fuel consumption per unit time is also minimized at the higher altitudes, the fuel penalties in absorbing delays at non-optimum altitudes are not large when using the Maximum Endurance Speed (MES) schedule, or even the LRC speed schedule. That is, when fuel must be burned to "buy time", rather than to "cover distance", then the choice of altitude is not nearly so important. For example, cruising for a 160 Klbs B727-200 at 10,000 feet, instead of at 33,000 feet, increases the fuel consumption per mile by about 67% at LRC speed: from about 18 lbs per mile to almost 30 lbs per mile. On the other hand, holding the same aircraft at 10,000 feet, instead of at 33,000 feet, increases the fuel consumption per minute only by about 10% at Maximum Endurance Speed (MES)*: from about 140 lbs per minute to about 155 lbs per minute. Figure 2-9 illustrates that at MES, the fuel penalty of "holding low" versus "holding high" is small, regardless of aircraft weight.

Since this chapter is about absorbing landing delays, fuel consumption per unit time is more important than fuel consumption per unit distance. As was first illustrated in Figure 2-5, and now in Figure 2-9, it is more important to minimize the time the aircraft must remain airborne (at 100 to 200 lbs per additional

* MES is also known as "Minimum Drag Speed".

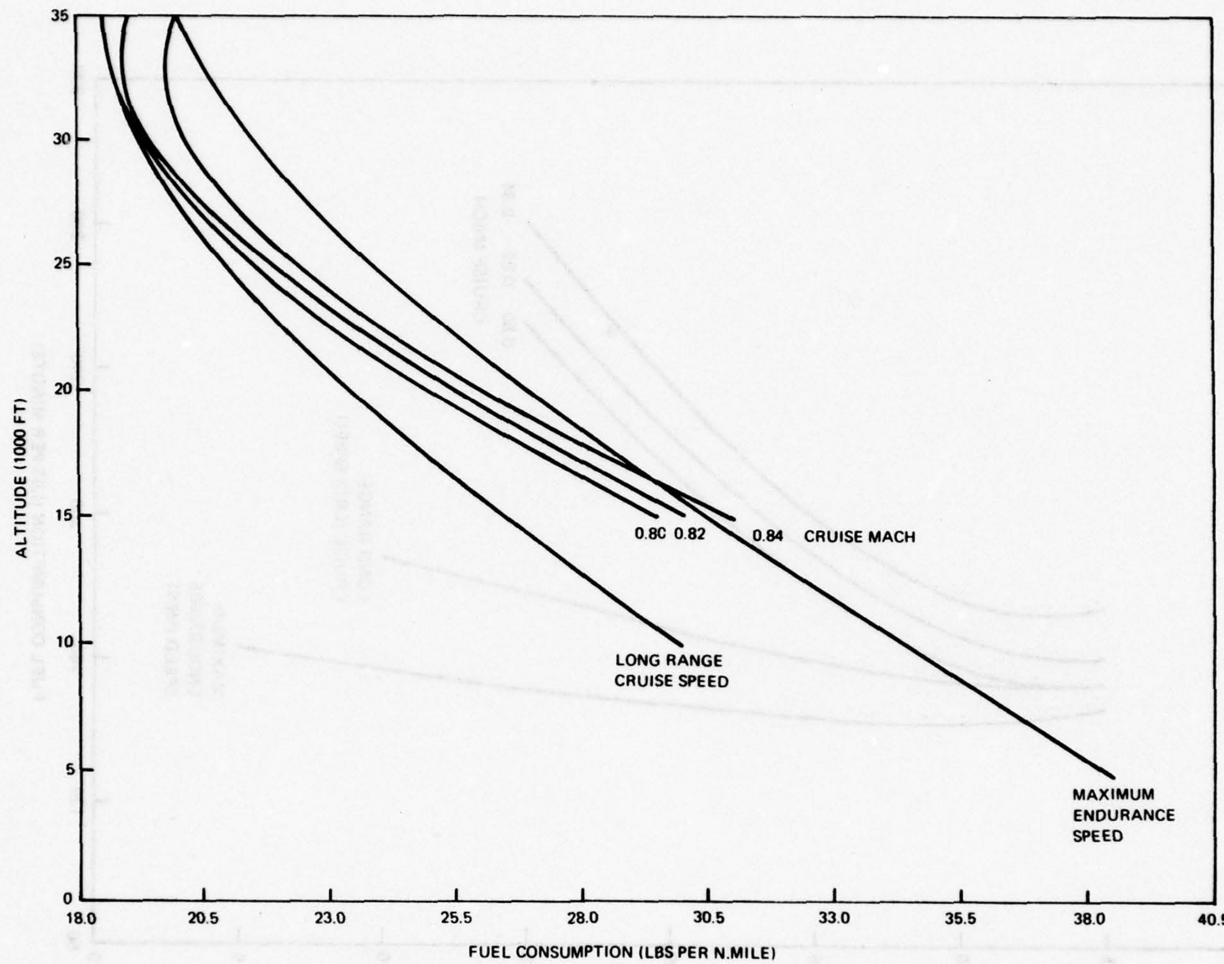


FIGURE 2-7
FUEL CONSUMPTION PER MILE IN CRUISE AT DIFFERENT ALTITUDES
(FOR A B727-200 @ 160,000 LBS & ZERO WIND, ISA)

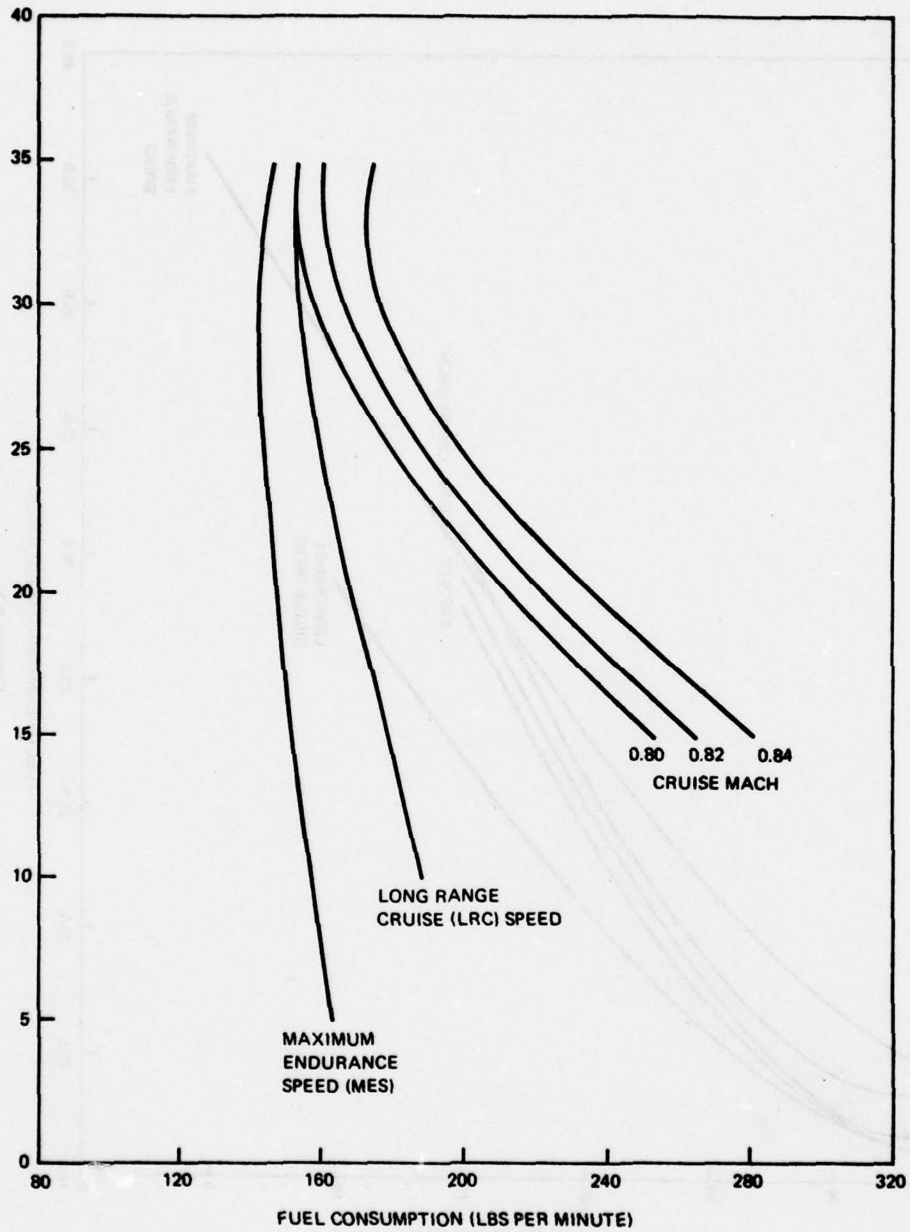


FIGURE 2-8
FUEL CONSUMPTION PER MINUTE IN CRUISE AT DIFFERENT ALTITUDES
(FOR A B727-200 @ 160,000 LBS AND ZERO WIND, ISA)

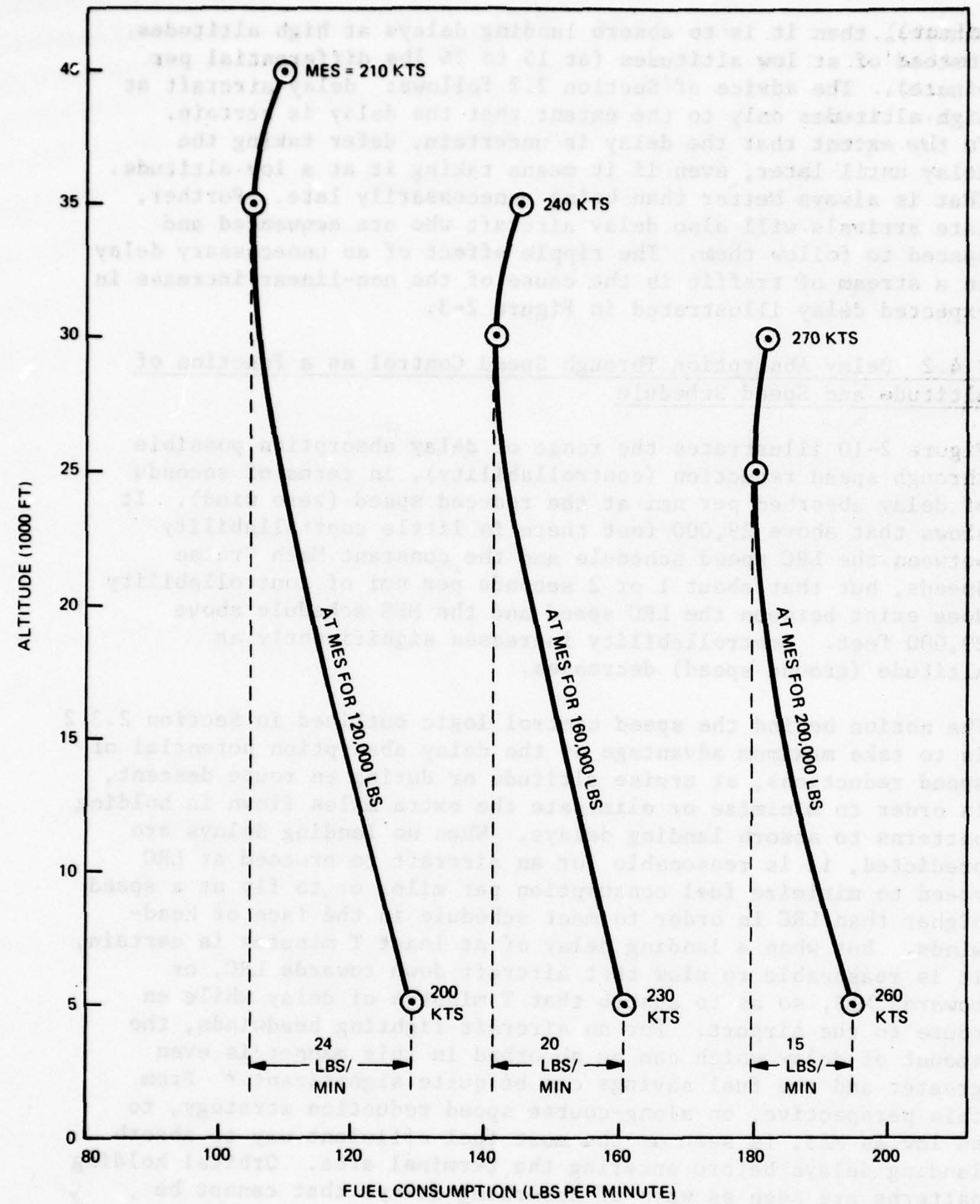


FIGURE 2-9
FUEL CONSUMPTION AT MAXIMUM ENDURANCE AND DIFFERENT ALTITUDES
(FOR A B-727-200 & ZERO WIND, ISA)

minute), than it is to absorb landing delays at high altitudes instead of at low altitudes (at 15 to 24 lbs differential per minute). The advice of Section 2.2 follows: delay aircraft at high altitudes only to the extent that the delay is certain. To the extent that the delay is uncertain, defer taking the delay until later, even if it means taking it at a low altitude. That is always better than being unnecessarily late. Further, late arrivals will also delay aircraft who are sequenced and spaced to follow them. The ripple effect of an unnecessary delay in a stream of traffic is the cause of the non-linear increase in expected delay illustrated in Figure 2-3.

2.4.2 Delay Absorption Through Speed Control as a Function of Altitude and Speed Schedule

Figure 2-10 illustrates the range of delay absorption possible through speed reduction (controllability), in terms of seconds of delay absorbed per nmi at the reduced speed (zero wind). It shows that above 29,000 feet there is little controllability between the LRC speed schedule and the constant Mach Cruise Speeds, but that about 1 or 2 seconds per nmi of controllability does exist between the LRC speed and the MES schedule above 29,000 feet. Controllability increases significantly as altitude (ground speed) decreases.

The notion behind the speed control logic outlined in Section 2.3.2 is to take maximum advantage of the delay absorption potential of speed reductions, at cruise altitude or during en route descent, in order to minimize or eliminate the extra miles flown in holding patterns to absorb landing delays. When no landing delays are predicted, it is reasonable for an aircraft to proceed at LRC speed to minimize fuel consumption per mile, or to fly at a speed higher than LRC in order to meet schedule in the face of head-winds. But when a landing delay of at least T minutes is certain, it is reasonable to slow that aircraft down towards LRC, or towards MES, so as to absorb that T minutes of delay while en route to the airport. For an aircraft fighting headwinds, the amount of delay which can be absorbed in this manner is even greater and the fuel savings can be quite significant.* From this perspective, an along-course speed reduction strategy, to as low as MES, is seen as the most fuel-efficient way to absorb landing delays before entering the terminal area. Orbital holding patterns are seen as ways of absorbing delays that cannot be predicted with certainty far enough in advance to be absorbed

* This argument is based in part on an unpublished analysis by Bela Collins of Metrek.

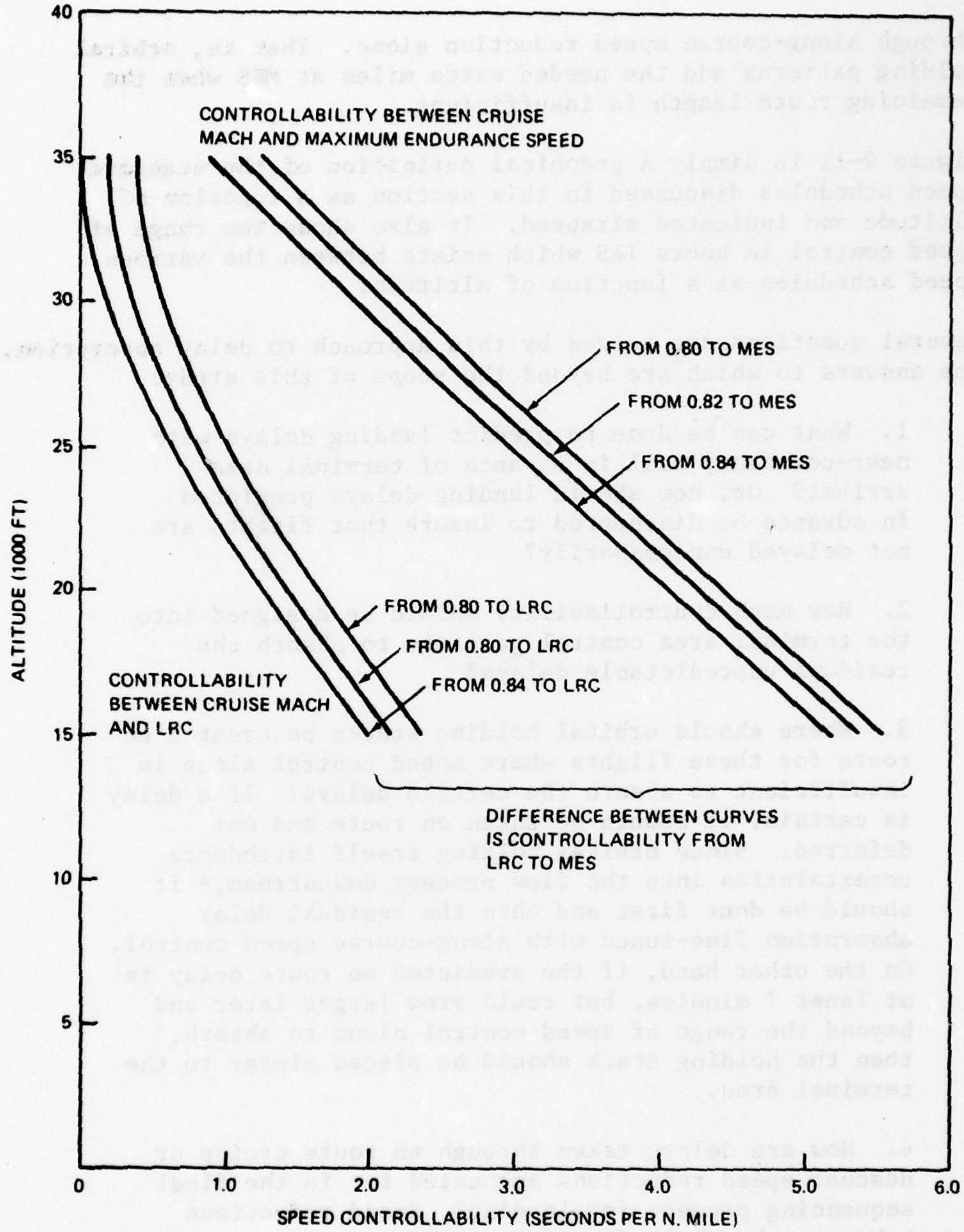


FIGURE 2-10
SPEED CONTROLLABILITY IN SECONDS PER MILE AT DIFFERENT ALTITUDES
(FOR A B-727-200 @ 160,000 LBS & ZERO WIND, ISA)

through along-course speed reduction alone. That is, orbital holding patterns add the needed extra miles at MES when the remaining route length is insufficient.

Figure 2-11 is simply a graphical definition of the standard speed schedules discussed in this section as a function of altitude and indicated airspeed. It also shows the range of speed control in knots IAS which exists between the various speed schedules as a function of altitude.

Several questions are raised by this approach to delay absorption, the answers to which are beyond the scope of this study:

1. What can be done to predict landing delays with near-certainty well in advance of terminal area arrival? Or, how should landing delays predicted in advance be discounted to insure that flights are not delayed unnecessarily?

2. How much controllability should be designed into the terminal area control geometry to absorb the residual unpredictable delays?

3. Where should orbital holding stacks be created en route for these flights where speed control alone is insufficient to absorb the certain delays? If a delay is certain, it should be taken en route and not deferred. Since orbital holding itself introduces uncertainties into the flow process downstream,* it should be done first and then the residual delay absorption fine-tuned with along-course speed control. On the other hand, if the predicted en route delay is at least T minutes, but could grow larger later and beyond the range of speed control alone to absorb, then the holding stack should be placed closer to the terminal area.

4. How are delays taken through en route cruise or descent speed reductions accounted for in the final sequencing process for landing? Speed reductions taken to absorb landing delays which cause aircraft

---

* At a turn rate of 1.5° per second, a flight which begins a holding turn cannot return to course for another 4 minutes. Thus, delivery to a metering fix from a nearby holding fix cannot be guaranteed within ± 2 minutes, given the clearance to depart the holding fix is always issued 2 minutes in advance.

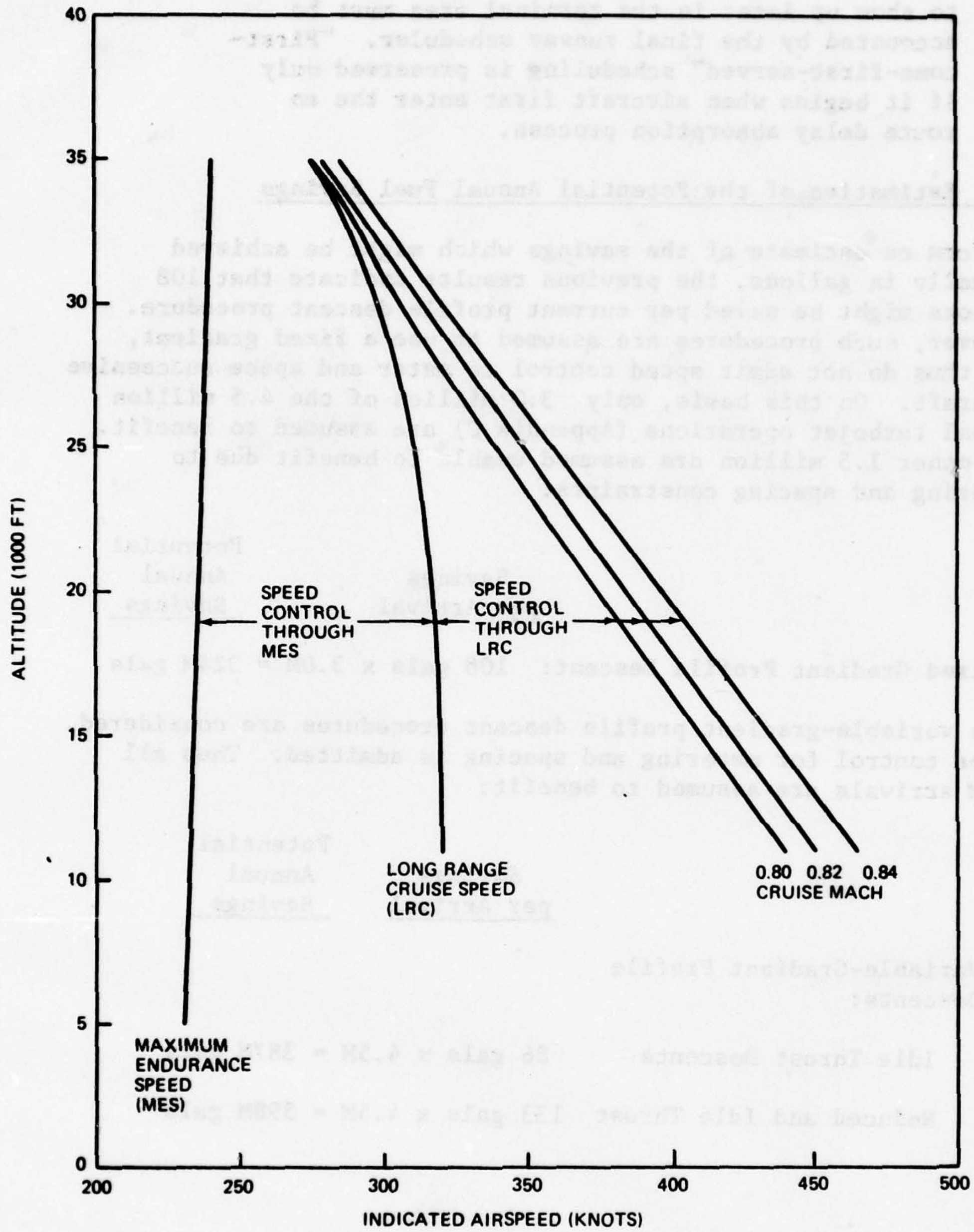


FIGURE 2-11
STANDARD AIRSPEED SCHEDULES VERSUS ALTITUDE AND INDICATED AIRSPEED
(FOR A B727-200 @ 160,000 LBS AND ZERO WIND, ISA)

to show up later in the terminal area must be accounted by the final runway scheduler. "First-come-first-served" scheduling is preserved only if it begins when aircraft first enter the en route delay absorption process.

2.5 Estimation of the Potential Annual Fuel Savings

To form an estimate of the savings which might be achieved annually in gallons, the previous results indicate that 108 gallons might be saved per current profile descent procedure. However, such procedures are assumed to use a fixed gradient, and thus do not admit speed control to meter and space successive aircraft. On this basis, only 3.0 million of the 4.5 million annual turbojet operations (Appendix C) are assumed to benefit. The other 1.5 million are assumed unable to benefit due to metering and spacing constraints:

	Savings per Arrival	Potential Annual Savings
Fixed Gradient Profile Descent:	108 gals x 3.0M =	324M gals

When variable-gradient profile descent procedures are considered, speed control for metering and spacing is admitted. Thus all 4.5M arrivals are assumed to benefit:

	Savings per Arrival	Potential Annual Savings
Variable-Gradient Profile Descents:		
Idle Thrust Descents	86 gals x 4.5M =	387M gals
Reduced and Idle Thrust	133 gals x 4.5M =	598M gals

3. PERMIT CLEANER, HIGHER SPEED APPROACH AND LANDING PROCEDURES

Approach and landing procedures for civil turbojet aircraft which delay or reduce the use of flaps through the use of higher speeds have been actively investigated and some used operationally in the past several years. Since flaps are drag-producing as well as lift-producing devices, delaying their use, or reducing the degree to which they are used, reduces the amount of thrust required to maintain the corresponding airspeed or altitude profile, thus reducing both the amount of fuel consumed during approach and landing and the amount of turbine noise laid down along the approach path.

The potential benefits of delayed or reduced-flap approach procedures, relative to more conventional approach procedures, can be addressed from at least two viewpoints. If the potential for competition with other traffic to use the runway is ignored, then the relative benefits can be computed on a single-flight basis, with the implication that these benefits multiply by the number of flights using such procedures.

On the other hand, if traffic interactions and competition for the same runway are taken into account, fuel and time tradeoffs can exist between ATC procedures for minimizing landing delays and these reduced or delayed-flap procedures. These tradeoffs and the net fuel savings which result are explored in this chapter.

3.1 Background on Delayed and Reduced-Flap Procedures

The "conventional" turbojet approach to an ILS runway can be characterized as:

1. Initially: Approach the airport at a constant desired or ATC-assigned speed, dropping flaps as required for stabilization to, say, 160 knots indicated. Level out at the published glide slope intercept altitude, typically 1800 feet above field elevation (AFE).

2. On Final Approach and Landing: First, capture and stabilize on the localizer course, and then capture the glide slope (GS). Establish the landing configuration (final flaps, gear down, stabilized landing speed) during glide slope capture (vicinity of the outer marker). For a 3° glide slope (about 320 feet per nmi) and a level approach altitude of 1800 feet, glide slope intercept would occur about 5.3 nmi from touchdown.

Note that flaps are deployed before glide slope capture, and that both full flaps and gear have been dropped by the time the glide slope is intercepted at 1800 feet. Reduced-flap and delayed-flap procedures are contrasted with this.

The guidelines for "reduced-flap" procedures as defined by the Air Transport Association (ATA), (Reference 3-1) are:

1. Initially: Approach the airport at as high an altitude as possible in accordance with current ATC procedures. Remain in a clean configuration and at or above 210 knots (no flaps or gear) for as long as possible.

2. On Final Approach: Proceed inbound from the final approach fix, or a similar distance for a visual approach, with flaps at one setting less than the final landing flaps setting planned for this particular landing. Plan to use the lowest landing flap setting which is permissible for the particular landing.

3. On Landing: Extend final landing flaps at the point on the final approach at which the aircraft is 1000 feet above field elevation, equipment performance permitting, in order to assure stabilization at not less than 500 feet above field elevation. For a 3° glide slope, final flaps would be drawn about 3 miles from touchdown.

"Delayed-flap" procedures have been developed by NASA/Ames (References 3-2 through 3-5). In these, appropriate advisories to the pilot regarding airspeed correction and when to deploy flaps and landing gear are computed and displayed dynamically by an on-board digital computer which is sensing air data, DME distance, and pilot-entered initialization data. The advantages of claimed for the computerized approach include greater consistency of operation, additional noise relief and fuel savings, greater safety by reducing pilot workload, providing an energy management and engine-out landing capability, and a wind shear detection and warning function. As in the previous procedures, however, thrust is reapplied so that stabilization is achieved at 1000 feet above the field, and the aircraft is landed in a conventional manner.

Table 3-1 summarizes two "reduced-flap" and two "delayed-flap" approach procedures tested by Boeing in their B727-200 simulator

TABLE 3-1
REDUCED FLAP AND DELAYED FLAP PROCEDURES SIMULATED BY BOEING FOR VISUAL METEROLOGICAL CONDITIONS

B727-200 (JT8D-9)	AIRLINE TYPICAL (REDUCED FLAP)		DELAYED FLAP APPROACHES	
	A-1	A-2	DFA-1	DFA-2
Initial Conditions	Level at 10,000 ft., 250 knots, 40 nmi from touchdown.			
To Capture Localizer and Glide Slope	Descend so as to slow to 150 knots upon reaching the GS intercept altitude of 3000'. Descent gradient is about 3° and will intercept 3000' about 3 nmi prior to GS intercept. Level and increase power to maintain 3000' and 150 knots until GS.		Same, except begin descent later so as to hold 220 kts. through GS capture.	Same as A-1, 2 except that IAS=200 knots during descent through GS capture.
Upon Reaching 5000' During Descent	Set 2° Flaps (at 200 kts)		Remain Clean (at 220 IAS)	Set 2° Flaps (at 200 IAS)
Upon Leveling at 3000'	Reset power to maintain 150 kts level until GS intercept.		Maintain 220 kts.	Maintain 200 kts.
Set Gear and Landing Flaps "Minus One" (25°)	At GS Capture (140 kts)	1 mile before OM	As computed to achieve stabilized landing speed at target altitude (500')	
Set Landing Flaps (30°)	At OM (1400')	At 140 kts		
Stabilized landing Speed Achieved*	About 4 nmi from touchdown (130 kts in still air or tailwind, 140 knots in 30 kts headwind).		About 2 nmi from touchdown (125 kts) in still air or tailwind, 140 knots in kts headwind).	

SOURCE: Boeing-Seattle Study, Reference 3-4.

(Reference 3-4). "Typical airline procedures" were devised to be representative of the current practices of five major airlines which responded to an ATA-sponsored survey. Though all airlines reporting were using procedures that generally met the intent of the ATA reduced-flap procedure, the flap schedules were sufficiently different to require two typical procedures, "A-1" and "A-2". The principal difference is that A-1 sets "landing flaps minum one notch" at glide slope capture (at about 3000 feet), while A-2 waits until one mile before the outer marker (about three miles closer to touchdown). Accordintly, A-2 is a bit more fuel-conservative than A-1, and comes closer to the ATA guidance to not set full landing flaps until 1000 feet AFE.

Two "delayed-flap" procedures were also devised. The principal difference is that "DFA-1" remains clean at 220 knots through glide slope capture, while "DFA-2" sets 2° flaps and maintains 200 knots through glide slope capture. Accordingly, DFA-1 is the more fuel-conservative.

3.2 Potential Fuel Savings on a Single-Flight Basis

Table 3-2 summarizes the relative fuel burns obtained by Boeing for a B727-200 using each of the four alternative procedures summarized in Table 3-1. Note that the initial condition point is 10,000 feet, 250 knots IAS, and 40 miles from touchdown. The table shows that the relative savings of the average delayed-flap procedure relative to the conventional procedures ranged from over 40 gallons in a 10 knot tailwind to about 120 gallons in a 30 knot headwind. These fuel savings represent 35% and 47%, respectively, of the conventional fuel burn.

Comparing the averaged reduced-flap procedures with the conventional procedure, the relative savings ranged between 10 and 20 gallons, tailwind to headwind. On this basis, the reduced-flap procedures now in use by the several of the major airlines do not realize more than 25% of the savings claimed for computer-assisted delayed flap approaches. It should also be noted that reduced-flap procedures are more commonly used in visual meterological conditions (VMC), than in instrument meterological conditions (IMC).

3.3 Higher Speed Approach Procedures and Automated Terminal Area Metering and Spacing Systems

To minimize landing delays under periods of demand, the ATC system provides "Metering and Spacing (M&S)" services to the landing aircraft. These services are typically provided for each primary airport by the Terminal Radar Approach Control

TABLE 3-2

EFFECTS OF WIND ON B727-200 FUEL SAVINGS REPORTED BY BOEING

	10 kt TAILWIND	STILL AIR	30 kt HEADWIND
Conventional	911 lbs.	1058 lbs.	1733 lbs.
	Δ = 72 (11 gals)	Δ = 86 (13 gals)	Δ = 125 (18 gals)
Reduced, A-1 A-2	873 805 } 839 lbs. avg.	1009 934 } 972 lbs. avg.	1662 1554 } 1608 lbs. avg.
	Δ = 240 (35 gals)	Δ = 304 (45 gals)	Δ = 684 (101 gals)
Delayed, DFA-1 DFA-2	556 644 } 600 lbs. avg.	614 723 } 668 lbs. avg.	820 1029 } 924 lbs. avg.
Potential Savings (Conventional Minus Delayed)	320 lbs. (46 gals)	390 lbs. (57 gals)	809 lbs. (119 gals)

SOURCE: Boeing-Seattle Study, Reference 3-4.

INITIAL CONDITIONS: 40 nmi from touchdown, 10,000' MSL, 250 knots IAS.

(TRACON) facility which has jurisdiction over the 30 miles or so of the airspace radially surrounding the airport. At present, these procedures are manually implemented by arrival radar controllers using distance criteria for spacing the aircraft, but automated metering and spacing systems are being developed which use time as the controlled variable.

The primary purpose of an automated metering and spacing system is to aid the controller in achieving the optimal spacing between arriving aircraft as they merge onto the final approach course. Runway throughput is maximized, and landing delays are minimized, when these arrivals are spaced just enough to insure that separation standards will not be violated anywhere between the merge point and the runway threshold. Consequently, there exists an optimum interarrival spacing, or interarrival time, at the gate for each pair of arrivals in the sequence. That optimum spacing is a function of (1) the separation standard (which is currently a function of the weights of both the leading and the following aircraft), (2) the speed differential between a pair of aircraft which can reduce the spacing between them somewhere along the common path to the runway (a function of the aircraft types, approach procedures in use, and individual differences), and (3) the ability of the controller to deliver aircraft to the merge point with the desired spacing (a function, in part, of the performance of the automated metering and spacing system supporting him).

The characteristics of the higher speed approaches which may affect the design or performance of automated metering and spacing systems are the:

1. <u>Higher desired speeds within the terminal area</u> prior to intercepting the final approach course, or localizer. Most turbojets cannot be operated in a clean configuration below 200 knots IAS or so. Given the current speed limit of 250 knots IAS below 10,000 feet MSL, it is to be expected that pilots desiring to conduct delayed or reduced-flap approaches would expect to traverse the terminal area to the final approach course somewhere between 200 and 250 knots IAS. This would limit the range of speed control available to 50 knots or so. Actual range is a function of the planned initial approach speed in the procedure.

2. <u>Higher initial speeds with significant deceleration along the final approach course</u>. The final approach course would be entered somewhere between

240 and 200 knots IAS for delayed-flap procedures (assume 220 knots), say 180 knots for reduced-flap procedures, rather than at 140 to 160 knots for conventional approach procedures (assume 160 knots).

All procedures would have the aircraft coverge to a common stabilized approach speed of 130 - 140 knots by some minimum altitude or distance from the runway for specified wind and visibility conditions.

3. Possibly higher glide slope intercept altitudes: The reduced or delayed-flap procedures which have been experimentally tried and/or flight-tested, and for which published data was available to the authors, have all used a glide slope intercept altitude of 3,000 feet AFE (References 3-2, 3-3, 3-4) instead of 1,800 feet AFE as for conventional approaches. However, unpublished data supplied upon request by NASA-Ames indicates that this higher intercept altitude may not represent a constraint on the design of such procedures for operational use (Reference 3-6). Accordingly, wherever in the subsequent analysis the 3,000 foot intercept is assumed, the results must be interpreted as illustrating what would happen if the intercept were in fact at this altitude, rather than at a lower one. This is important because the altitude at the intercept determines the length of the "common path" between the last merge point onto the final approach course, or "ATC gate", and the runway threshold.*

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* Using current radar procedures, the arrival controller may use speed and heading adjustments for sequencing and spacing an aircraft until just before it intercepts the ILS glide slope and begins its final descent to the runway. From that point on, each arrival normally proceeds on its own to land and exit the runway (decisions to abort the approach by the pilot or ATC excepted).

In the following analysis, the location of the last point for flide slope interception is a function of the particular approach procedure assumed. The term "ATC gate" is used to denote that point beyond which the aircraft proceeds on its own to reach, land, and exit the runway. The significance of this is that, without further spacing corrections by ATC, the effect of speed differences between successive aircraft on inter-arrival spacings is proportional to the length of the common path.

3.4 The Impact of Higher Speed Approaches on Metering and Spacing System Design and Controllability

The range of adjustment the system has in controlling an aircraft's flight time to the ATC gate is referred to as the "controllability" of the system. For example, if ATC can use both speed control and path length control to adjust the flying time to the ATC gate, then the controllability range is defined as $(T_l - T_s)$ where:

T_L = The flight time over the longest path at the slowest speed.

T_S = The flight time over the shortest path at the highest speed.

The path length is measured from the point on the approach path where the speed reductions and/or path length adjustments can commence.

Path control can be achieved by either:

1. "Trombone" shaped, variable-length downwind courses where the controller can turn "late" aircraft "short" to the final approach course, and can maintain "early" aircraft on a "long" downwind until the needed delay can be absorbed.

2. Triangular-shaped "delay fans" over which the aircraft is placed on ATC-selected headings which lie between the shortest "direct" path to the next control point on the approach path (traverses one side of the triangle) and the longest "dog-leg" path (traverses two sides of the triangle) to the next control point.

The use of delay fans in the design of metering and spacing control geometries and computer algorithms was first investigated in the early 1960's (Reference 3-9) and later used in the design of a proposed system for Denver's Stapleton airport (Reference 3-8). In both cases, two delay fans were used: one on the downwind leg for sequencing and coarse spacing control, and one on the base leg for fine spacing control. This type of design is referred to in the literature as the "TALL" geometry, which stands for "Transition/Approach/Local/Landing" control.

Analysis and simulation has shown that the TALL geometry is technically superior in delivering aircraft according to schedule to the last merge point, or "ATC gate", on the final approach course (See Section 3 in Reference 3-8 or Reference 3-9).

Because of the importance of precise delivery of aircraft to the final approach course with the desired spacings, given runway throughput is to be maximized under periods of moderate-to-high demand, the following analysis will be limited to the subject of TALL (delay fan) metering and spacing geometries.

The left-hand side of Figure 3-1 illustrates a TALL geometry designed for conventional geometry are noted:

1. A reduced range for speed control in the terminal area is available. Reason: the maximum speed below 10,000 feet is assumed to be limited to 250 knots. The minimum speed is assumed to be determined by the specified approach procedure speed at glide slope capture (160 knots for conventional versus 220 knots assumed for delayed-flap, and 180 knots assumed for reduced-flap).

2. In an attempt to retain the same time controllability given the higher average speeds, the delay fans are larger, assuming that the required additional airspace is available (this may present a problem in some terminal areas).

3. The ATC gate is placed at 11 miles, instead of at 8 miles. Reason: A glide slope intercept altitude of 3,000 feet is assumed, instead of 1,800 feet, and 1.5 to 2 miles are allowed for ILS localizer acquisition prior to GS capture.

4. The length of the "dog-leg" side of the downwind delay fan is constrained by the turn radii needed to turn base and still intercept the final approach course <u>reasonably close to the ATC gate</u>. Delivery accuracy decreases as the aircraft intercept the final approach course farther away from the threshold (because the aircraft fly "open loop" longer distances, thereby accumulating larger flying time deviations).

5. The turns at higher speed from base to final can preclude the effective use of the "final path stretching area" achieving any control. As illustrated in Figure 3-1, the final turn is designed as a limit so that the turn-to-final cannot be delayed any further past the turn-to-final arc (dotted), without compromising localizer capture.

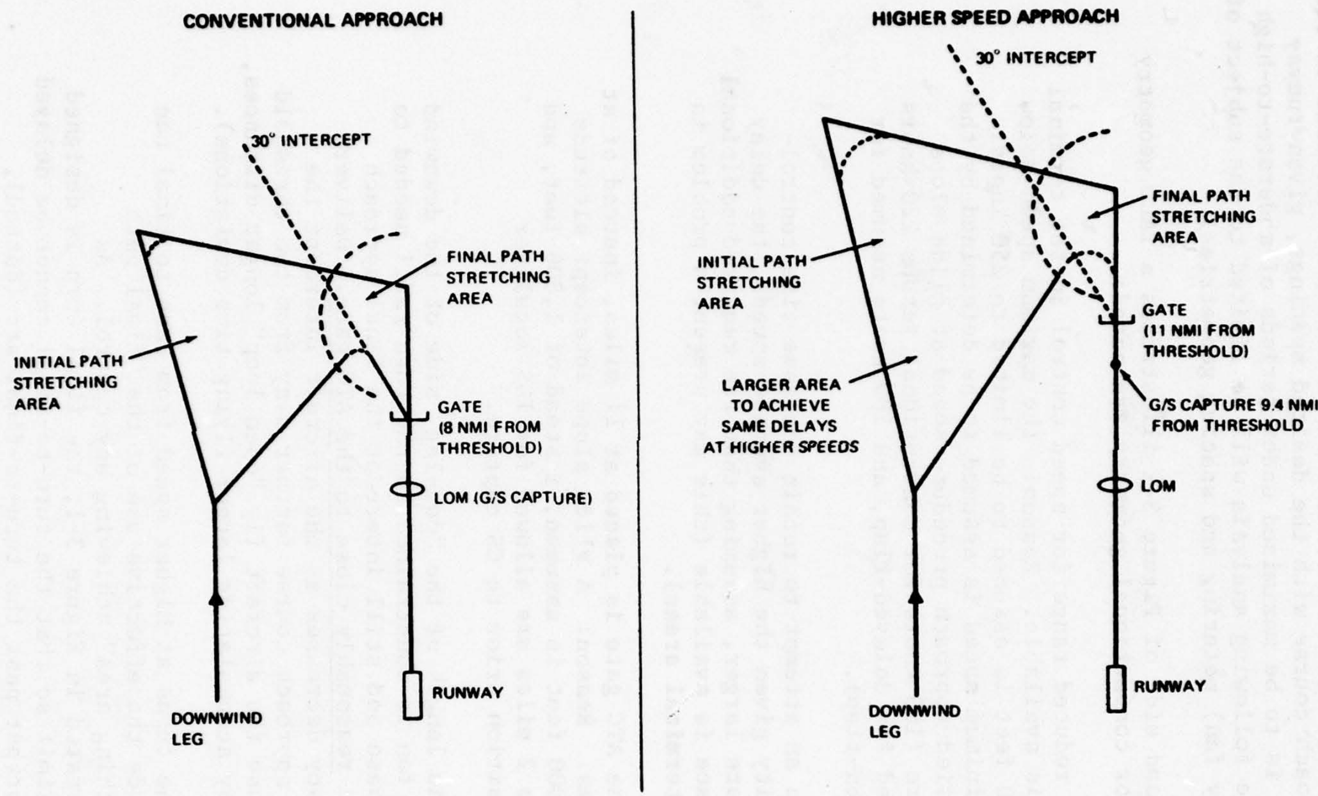


FIGURE 3-1
VECTORING AREA CONTROL GEOMETRIES FOR HIGHER SPEED APPROACHES

Table 3-3 summarizes the results of computing the controllability achievable within the basic TALL geometry for conventional approaches and within the modified TALL geometry for the higher speed approaches.

The table shows that some controllability is lost between conventional and reduced-flap approach procedures in the vectoring area (about 40 seconds), while more is lost between conventional and delayed-flap approach procedures (about 100 seconds). At a throughput of 35 arrivals an hour (one aircraft crossing the ATC gate every 103 seconds), a loss of 40 seconds in controllability would probably not affect ATC's ability to re-sequence, but a loss of almost a full slot (100 seconds) could.

An additional problem in the case analyzed is that all of the controllability in the final path-stretching area has been lost for the example delayed-flap approaches. That is, if the turn from downwind is not perfectly timed and the aircraft is somewhat early arriving the turn-arc on the final approach course, thus closing on the aircraft ahead on final, no capability is left to delay the former's turn onto final without overshooting the localizer course. The result: a missed approach would be required. Conversely, if the aircraft is late and cannot be corrected, the following aircraft may be forced to miss its approach.

3.5 Possible Impacts of Higher Speed Approaches on Runway Capacity and Delays

The following analysis examines the sensitivity of runway capacity to:

1. A longer common path from the ATC gate to the runway,

2. the mixing of higher speed and conventional procedures, and

3. the inclusion of small piston and heavy aircraft in the arrival sequence when higher speed approaches are being considered.

The key input parameters and resultant capacity estimates for each case are tabulated in Table 3-4. The runway capacity estimates were generated using the analytic model described in Appendix A.2.

TABLE 3-3

CONTROLLABILITY ACHIEVED FOR DIFFERENT APPROACH PROCEDURES AND CONTROL GEOMETRIES

ROUTE SEGMENT	CONTROLLABILITY (SECONDS) CONVENTIONAL APPROACH	EXAMPLE REDUCED-FLAP APPROACH	EXAMPLE DELAYED-FLAP APPROACH
INITIAL PATH STRETCHING AREA	197	181	175
FINAL PATCH STRETCHING AREA	73	49	0
FINAL APPROACH	0	0	0
TOTALS	270	230	175

HIGHER SPEED GEOMETRY

TABLE 3-4
SENSITIVITY OF RUNWAY CAPACITY TO PROCEDURE MIX,
AIRCRAFT MIX, AND GLIDE SLOPE INTERCEPT POINT

	SAME TURBOJET PROCEDURE NO PISTON OR HEAVY AIRCRAFT			MIXED TURBOJET PROCEDURES NO PISTON OR HEAVY AIRCRAFT		SAME TURBOJET PROCEDURE PISTON AND HEAVY AIRCRAFT INCLUDED		
AIRCRAFT MIX*	100 C	100 R	100 D	40 C, 60 R	40 C, 60 D	5 L, 10 M, 75 C, 10 CH	5 L, 10 M, 75 R, 10 RH	5 L, 10 M, 75 D, 10 DH
GATE APPROACH SPEEDS (KTS)	160	180	220	160, 180	160, 220	135, 160, 160, 160	135, 160, 180, 180	135, 160, 220, 220
AVERAGE FINAL SPEEDS (KTS)	130	130	130	130, 130	130, 130	95, 120, 130, 130	95, 120, 130, 130	95, 120, 130, 130
FINAL APPROACH PATH (NMI) GLIDE SLOPE INTERCEPT (NMI)	8.0 6.0	11.0 9.5	11.0 9.5	11.0 9.5	11.0 9.5	8.0 6.0	11.0 9.5	11.0 9.5
IFR MINIMUM SEPARATION (NMI)	3	3	3	3	3	3,5,5,6	3,5,5,6	3,5,5,6
SPEED ERROR AFTER GATE (ONE SIGMA KNOTS)	5	5	6	5	6	5	5	5
INTERARRIVAL ERROR AT GATE** (ONE SIGMA SECONDS)	8	8	8***	8	8***	8	8	8***
RUNWAY CAPACITY ESTIMATE**** (LANDINGS PER HOUR)	35	33	35	33	32	31	29	30

* C - LARGE TURBOJETS USING CONVENTIONAL LANDING APPROACHES
R - LARGE TURBOJETS USING REDUCED-FLAP APPROACHES
D - LARGE TURBOJETS USING DELAYED-FLAP APPROACHES
L - SMALL SINGLE ENGINE AIRCRAFT LANDING CONVENTIONALLY
M - SMALL TWIN ENGINE AIRCRAFT LANDING CONVENTIONALLY
CH - HEAVY TURBOJETS LANDING CONVENTIONALLY
RH - HEAVY TURBOJETS USING REDUCED-FLAP APPROACH
DH - HEAVY TURBOJETS USING DELAYED-FLAP APPROACH

** ASSUMES THE DELIVERY ACCURACY EXPECTED OF ADVANCED METERING AND SPACING AUTOMATION

*** ASSUMING AIRSPACE FOR CONTROL IS AVAILABLE TO ACHIEVE THIS ACCURACY

**** RUNWAY OCCUPANCY CONSTRAINTS NOT CONSIDERED

With regard to the assumed parameters:

1. The effect of the losses in controllability identified in the previous section were specifically excluded. To do this, it was optimistically assumed that the precision of an advanced metering and spacing system in delivering aircraft to the gate could be achieved in all cases (8 seconds, one sigma).

2. Speeds along the final approach course are assumed to be within 5% (one sigma) of the indicated airspeed schedule.

The following cases are analyzed:

Case 1 - Same turbojet procedures; no small or heavy aircraft: The IFR minimum separation standard is 3 miles; all arrivals use the same nominal approach speed profile. Thus the planned spacing between aircraft need only account for the separation standard, the statistical inter-arrival delivery error at the gate, and the statistical speed compression possible due to individual differences after the gate. The The gate is at 8 miles in the conventional case and at 11 miles in the reduced-flap and delayed-flap cases.

The first major column of Table 3-4 shows that, relative to a capacity of 35 aircraft per hour for conventional approaches, a capacity loss of two arrivals per hour occurs with the reduced-flap approach procedures. However, half of this loss is regained when delayed-flap approaches are used. The reason for this result is that moving the ATC gate out from 8 miles to 11 miles increases the distance over which speed errors can integrate, but the delayed-flap approaches are conducted at a speed high enough to partially offset this loss. That is, the effect of the increase length of the common path is partially offset by a reduction in the time spent traversing it at the higher speed.

If the gate need not be moved out, or if the speed error for delayed-flap approaches can be held tighter than 5% of indicated, some

capacity increase with the higher speed approaches could result.

Case 2 - <u>Mixed turbojet procedures; no small or heavy aircraft</u>: The separation standard is again 3 miles, but the gate is at 11 miles in both cases since reduced-flap or delayed-flap procedures are being mixed with conventional procedures using the higher speed control geometry (see the second major column on Table 3-4). Since reduced flap and conventional procedures do not greatly differ in speed, the capacity is unchanged from the 100% reduced-flap case. If instead the gate were at 8 miles, the capacity would be unchanged from the 100% conventional case. This case is probably representative of the situation today were a mix of conventional and reduced flap procedures are being used.

When delayed-flap procedures are mixed with conventional procedures, a capacity loss of 2 arrivals per hour occurs relative to the 100% delayed-flap case. Here the speed difference between procedures is sufficient to cause unwanted opening of the interarrival spacing at the runway threshold when a conventional approach follows a delayed-flap approach, given minimum separation was established at the merge point (assumed to be the ATC gate). Since the opportunity for opening pairs is greatest when the number of aircraft conducting each type of approach is equally divided, the 50% conventional, 50% delayed-flap mix represents the worst case. As the mix shifts towards more of one kind of approach procedure or the other, the capacity would increase from the 32 per hour found in this case towards either the 34 per hour found in the 100% delayed-flap case or towards the 100% conventional case, but with an 11 mile gate (value not computed).

The case of mixed conventional and delayed-flap approach procedures is probably indicative of what would happen if some air carriers equipped their aircraft for delayed-flap procedures, but others did not, and equipage was not made a prerequisite for runway use.

Case 3 - Same turbojet procedure, piston and heavy aircraft included: In these cases, 5% and 10% of the arrivals are assumed to be single and twin engine piston aircraft, respectively, which use conventional approach speeds for aircraft of their type. Another 10% of the arrivals are assumed to be heavy turbojets. Because of the wake vortex potential, the minimum separation standards now became:

		TRAIL AIRCRAFT		
		Small	Large	Heavy
LEAD AIRCRAFT	Small	3	3	3 nmi
	Large	4	3	3
	Heavy	6	5	4

Where the weight descriptions of aircraft are:

Heavy > 300,000 lbs.
Large > 12,500 lbs.
Small ≤ 12,500 lbs.

All turbojet aircraft, large and heavy, are assumed to conduct the same type of approach procedure - conventional, reduced-flap, or delayed-flap (see the third major column in Table 3-4). Lower capacities are found than in the previous cases due to the wider speed differentials possible for opening pairs at the threshold, and to the occasional need for the wider wake vortex spacings. Still, the conventional geometry with the 8 mile gate yields the highest capacity at 31 per hour, and the higher speed geometry with the 11 mile gate lowest at 29 per hour.

Due to the high percentage of aircraft equipped for the higher speed delayed-flap procedures (85%), a capacity higher than 30 might have been expected. However, the small percentage of piston aircraft (15%) is sufficient to keep the capacity below that of the previous "worst case" of 50% conventional, 50% delayed-flap when piston aircraft were excluded.

3.6 Impact of Runway Throughput Losses on Net Fuel Savings

Runway throughput can be lost relative to conventional approach procedures for any of several identified reasons: losses in controllability, wider speed mixes, or a longer path from gate to runway. Whatever the reason, such a loss translates into

increased landing delays above some demand level. It becomes important to ask: how much would an incremental loss in runway capacity increase the expected delay of arriving aircraft as a function of demand? Above what demend level would the fuel saved by the use of reduced or delayed-flap approaches be offset by the increase in expected delay?

For example, assume that a runway capacity of 35 aircraft per hour with the conventional approach geometry and procedure is reduced to a capacity of 33 aircraft per hour using the higher speed approach geometry and procedures. Landing delays as a function of demand, obtained from the landing delay model described in Appendix A-1, are plotted for runway capacities of 35 and 33 aircraft per hour in Figure 3-2. These results are based on input data which represents a current Denver terminal area geometry, permissable inter-arrival spacings over the final approach course, and a uniform distribution of arrivals at the metering fixes, with an en route metering delivery accuracy of one minute (one sigma).

Figure 3-2 shows that below a demand of about 20 arrivals per hour, some small delays should be expected for spacing, but there is no significant difference in the expected delay as a function of which approach procedure is used. Between 20 to 30 arrivals per hour, the difference between approach procedures begins to have an impact on delays, but it is not very significant. When a sustained demand for the runway exceeds 90% of capacity (30 ÷ 33), then arriving aircraft conducting high speed approaches could expect a significantly larger landing delay. At a demand level of 35 an hour, the expected delay is in excess of two minutes for a capacity of 33 per hour versus less than one minute for a capacity of 35 per hour. This increase in expected delay will reduce the net fuel savings from the higher speed approaches.

Figure 3-3 illustrates this fuel tradeoff using the assumption that the expected fuel benefit of a reduced-flap approach might be 131 lbs.* At a demand level below 20 arrivals per hour, that benefit would be obtained. However, between 20 and 30 arrivals per hour, that benefit would be somewhat offset by the small delay differential that exists. At a demand of about 30 random arrivals per hour, the increase in expected delay has reached a

* This is the difference between the fuel burns for a B727 as measured from 15 miles and 3,000 feet to touchdown reported by Reference 3-3:

conventional approach = 769 lbs.
reduced-flap approach = 638 lbs.
131 lbs.

The same difference reported for a delayed-flap approach was 381 lbs.

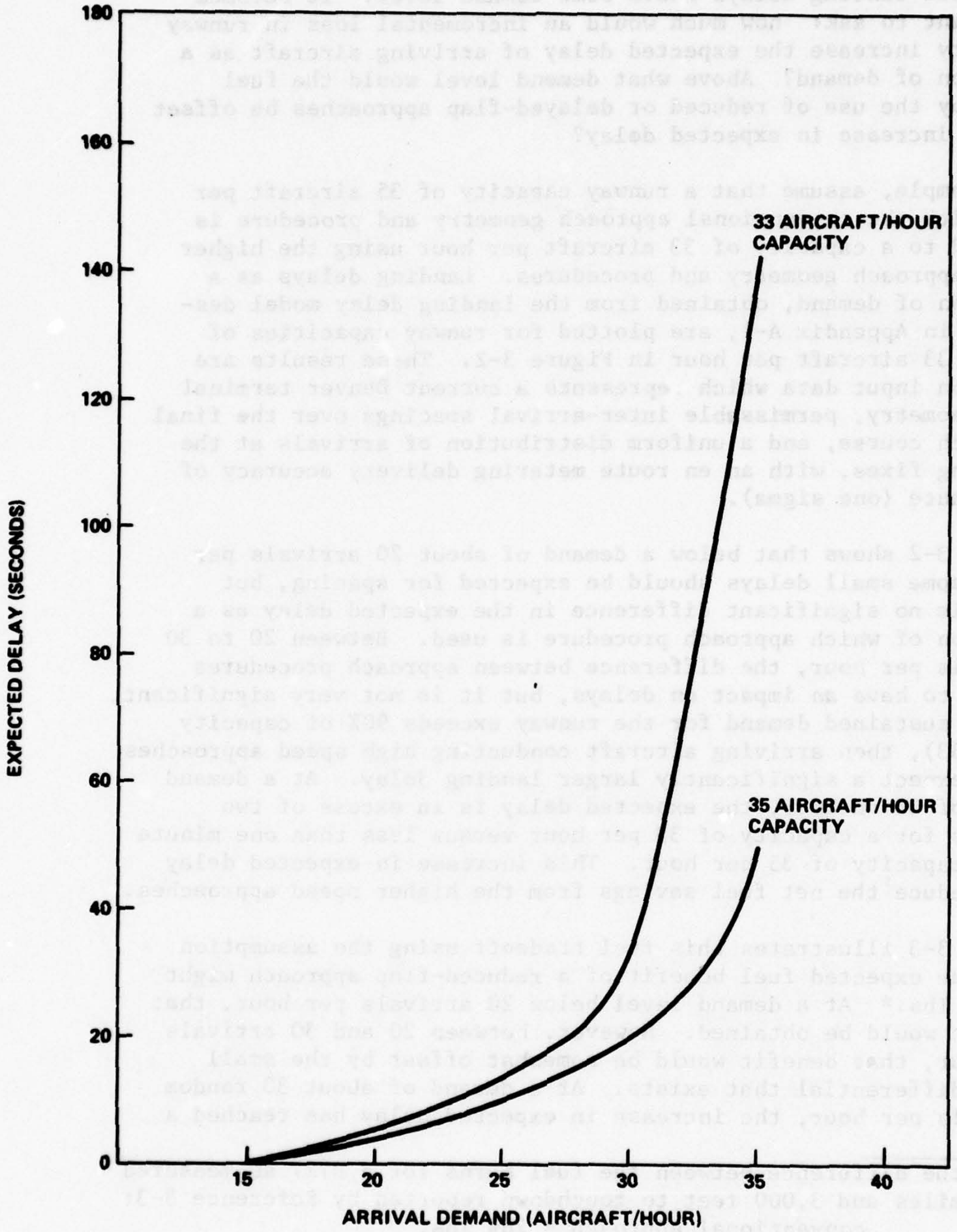


FIGURE 3-2
EXPECTED LANDING DELAYS AS A FUNCTION OF ARRIVAL DEMAND

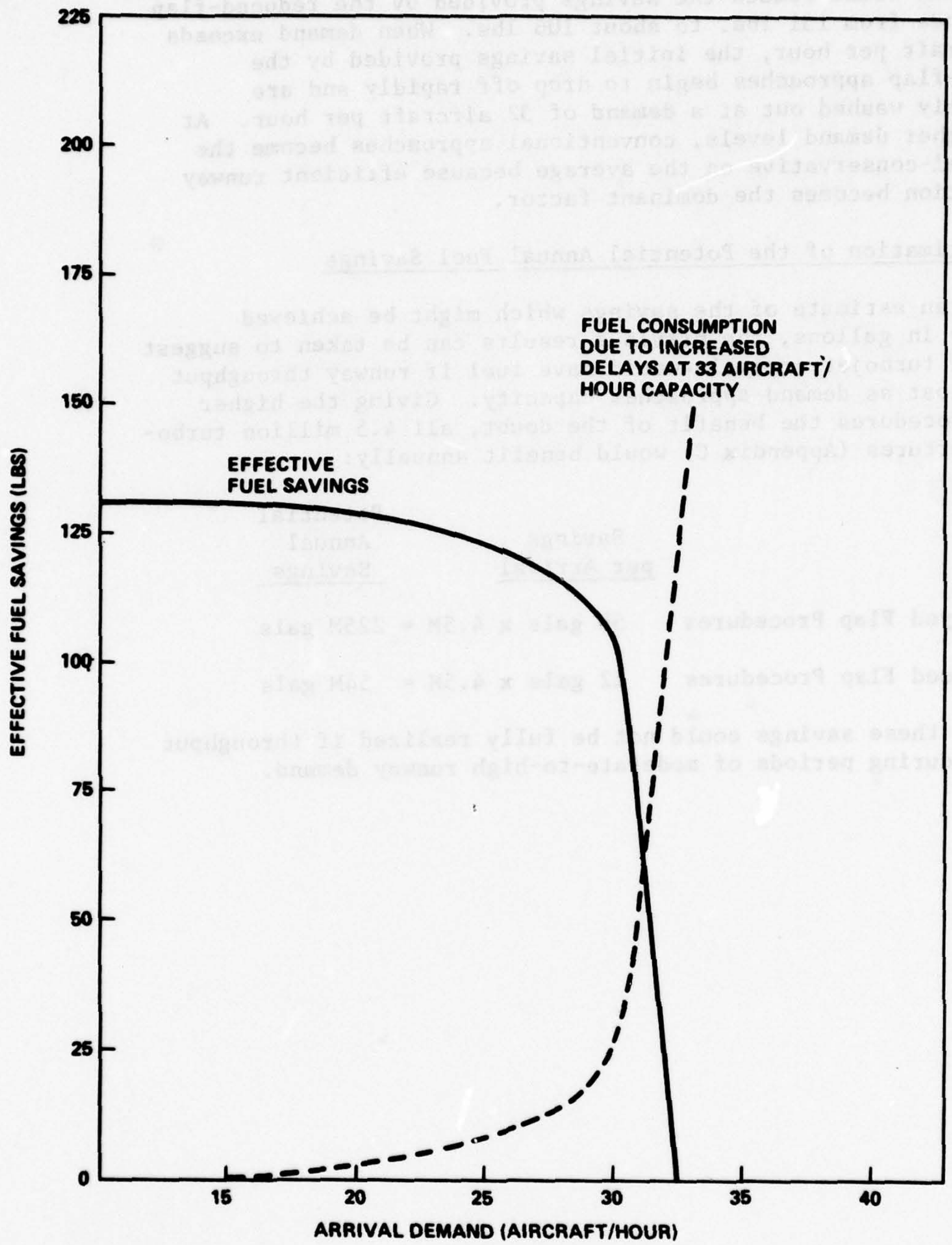


FIGURE 3-3
NET FUEL SAVINGS AS A FUNCTION OF ARRIVAL DEMAND

level that would reduce the savings provided by the reduced-flap approaches from 131 lbs. to about 106 lbs. When demand exceeds 30 aircraft per hour, the initial savings provided by the reduced-flap approaches begin to drop off rapidly and are completely washed out at a demand of 32 aircraft per hour. At even higher demand levels, conventional approaches become the more fuel-conservative on the average because efficient runway utilization becomes the dominant factor.

3.7 Estimation of the Potential Annual Fuel Savings

To form an estimate of the savings which might be achieved annually in gallons, the previous results can be taken to suggest that all turbojet arrivals would save fuel if runway throughput is not lost as demand approaches capacity. Giving the higher speed procedures the benefit of the doubt, all 4.5 million turbojet departures (Appendix C) would benefit annually:

	Savings per Arrival		Potential Annual Savings
Delayed Flap Procedures	50 gals x 4.5M	=	225M gals
Reduced Flap Procedures	12 gals x 4.5M	=	54M gals

However, these savings could not be fully realized if throughput is lost during periods of moderate-to-high runway demand.

4. LOWER THE ALTITUDE RESTRICTION ON THE 250 KNOT SPEED LIMIT

Currently, aircraft may not be operated below 10,000 feet MSL at an indicated airspeed of more than 250 knots. With the increase infuel prices, interest has been generated in removing this speed limit, at least within Terminal Control Areas (TCA's) where Stage III radar separation and sequencing services are provided to all aircraft. The basic argument is that fuel and time savings can be achieved without compromising flight safety within such areas.

The purpose of this chapter is to assess the fuel and time savings potential of removing the 250 knot rule from some or all of the altitudes below 10,000 feet within Terminal Control Areas. A further purpose is to put these potential savings into perspective relative to the other approaches considered by this report. The background of the 250 knot rule is first discussed briefly to put the proposals for its removal into context, but no assessment of these proposals from the standpoint of separation assurance is attempted.

4.1 Background on the 250 Knot Rule and the Proposals to Remove It

According to the current Federal Air Regulations, 14 CFR 91.70, "...no person may operate an aircraft below 10,000 feet MSL at an indicated airspeed of more than 250 knots...", within Terminal Control Areas (TCAs) and in en route airspace. In airspaces underlying TCAs, within VFR corridors through TCAs, or within airport traffic areas*, no person may operate an aircraft at an IAS of more than 200 knots. The 250 knot rule has been in effect since December 15, 1967. The 200 knot rule near TCAs was added April 28, 1973.

The 250 knot speed limit was first imposed in December 1961 and was then applied only within 30 miles of the destination airport. It was one consequence of a collision in December 1960 over Staten Island, N.Y., involving a United DC-8 and a TWA Constellation. The investigating board found that "A contributing factor was the high rate of speed of the United DC-8 as it approached the Preston intersection..." at about 5000' MSL in preparation for an approach to JFK International (Reference 4-1). Since then, the rule was broadened by dropping the 30 mile condition.

An FAA study of near mid-air collisions published in 1969 (Reference 4-2) showed that "... high rates of closure (300 knots or

* Airport traffic areas are established within five miles and below 3000' AGL of each airport with a control tower.

better) without some form of alerting assistance almost preclude effective 'see and avoid' operations". At that time, "some form of alerting assistance" was often not available where high performance turbojet aircraft, usually operating IFR, mixed with slower piston aircraft, usually operating VFR. Since then, some 21 Terminal Control Area (TCAs) and about 50 Terminal Radar Service Areas (TRSAs) have been established which provide radar separation and sequencing services to both IFR and VFR aircraft, VFR participation being mandatory in TCAs. It can be argued that the presence of such services make the 250 knot speed limit unnecessary for safety, and undesirable at or above 5 thousand feet where fuel and time efficiencies for turbojets are impacted.

According to Reference 4-3, three proposals were made to the FAA-sponsored 1975-76 Operations Review Conference with regard to easing the speed limit restrictuions of 14 CFR Part 91.70. Two of these proposals would have excluded flights inside TCAs from the 250 knot rule, 91.70(a), and one would have removed the 200 knot limitation of 91.70(c), thereby lifting the speed limit to 250 knots below TCAs and inside VFR corridors through TCAs. The FAA rejected lifting the 250 knot rule inside TCAs because "...the FAA does not believe the resultant increased speeds would enhance ATC procedures in high density terminals."

More recently, the ATA has proposed to the FAA that a new rule be added to 91.70: "Unless otherwise required by ATC, an aircraft may be operated in excess of 250 knots.." when operating:

1. At or above 5000' AGL, and

2. Within the confines of a TCA having a designated ceiling of 10,000' MSL or more.

This proposal makes a distinction between the safety problems of the higher speeds in the terminal area below 5000' where "...ATC is sorting out departures and sequencing arrivals..." and above 5000' where most users stand to gain by relaxing the speed limit (Reference 4-4).

4.2 Potential Fuel and Time Savings on a Per-Flight Basis

If it were possible to arrive and depart a TCA-served airport unrestricted in both speed and altitude, then two types of benefits could be anticipated, relative to the more restrictive regime:

1. A fuel saving since less flight time is spent at the lower speeds and altitudes where turbojet aircraft are less efficient.

2. A flight time saving since at the higher speeds, the total time is reduced.

On a single flight basis, landing delays and other factors due to traffic can be ignored, and the potential benefits of lifting the 250 knot speed limit can be computed.

Two different methods of computing the fuel and time savings were developed. The first analyzed the savings for arrivals using a particular profile descent procedure then used during low traffic periods at Chicago's O'Hare airport and is described in Section 4.2.1. The second parametrically analyzed the benefits on both departure and arrival for different constant speed schedules and is described in Section 4.2.2.

4.2.1 Estimate of Savings to Arrivals Using the Romeo Descent Procedure

The "Midnight Romeo" profile descent procedure was used by high altitude arrivals to runway 14R at Chicago's O'Hare airport. Its use was restricted to periods of low traffic when there was little contention for the runway. Figure 4-1 shows the procedure in profile for the arrival feeder fix "Plano" (southwest of the airport) to the runway threshold. For the analysis, if it is assumed that:

1. The aircraft makes the profile descent at a constant 350 knots IAS, and that

2. The aircraft must level for about 10 nmi in order to slow from 350 knots to 250 knots, and that

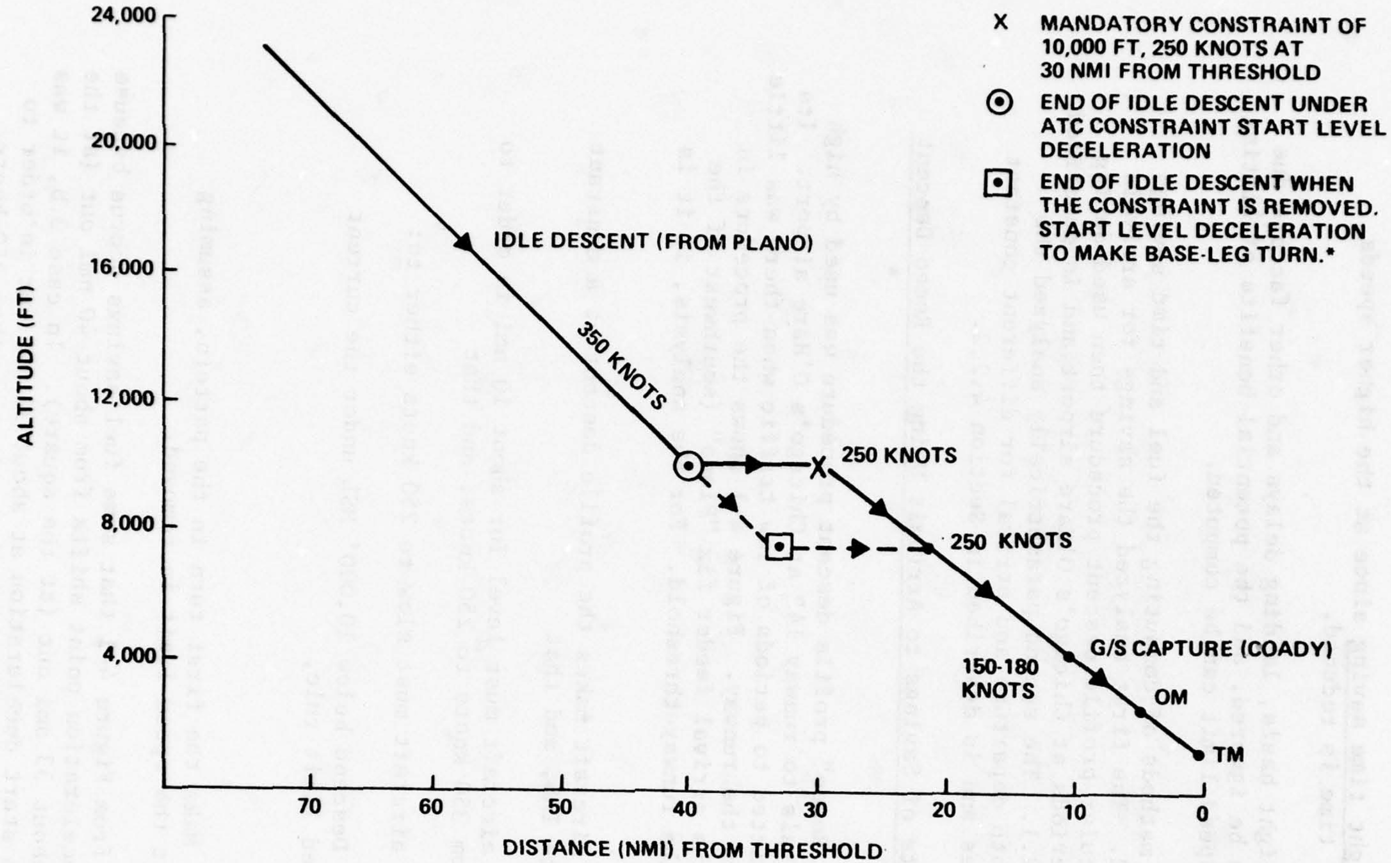
3. The aircraft must slow to 250 knots either to:

   a. Descend below 10,000' MSL under the current speed limit rule,

   or to:

   b. Make the first turn in the pattern, assuming that the speed limit is removed.

It is clear from Figure 4-1 that some fuel savings accrue because the start-deceleration point shifts from about 40 nmi out (at the circle) to about 33 nmi out (at the square). In case 3.b, it was necessary to start deceleration at about 33 nmi out in order to initiate the turn towards "Coady" at not more than 250 knots.



Source: Reference 4-3

FIGURE 4-1
A DESCENT PROFILE WITH AND WITHOUT THE 250 KNOT SPEED LIMIT

Figure 4-2 illustrates all published approach paths to runway 14R using the Midnight Romeo profile descent. The locations of start-deceleration point, "before" and "after" lifting the speed limit, are marked as in Figure 4-1. From inspection of Figure 4-2, it is clear that the higher speed distance added by removing the speed limit is less than 10 miles for all approaches. The fuel savings were computed and are shown in Table 4-1 to be less than 10 gallons per arrival.

The corresponding time savings are all less than one minute.

The fuel-burn data for this analysis was developed from the "Descent Performance Table" for a B727-225A aircraft, powered by three Pratt and Whitney JT8D-15 engines. (Reference 6-3).

4.2.2 Parametric Analysis of the Potential Savings for Both Arrivals and Departures

To generalize the results of the previous section, and to obtain the potential savings from lifting the 250 knot speed limit rule for departures, a parametric analysis was performed using the fuel burn model described in Appendix B. This model assumes that the aircraft is powered by three Pratt and Whitney JT8D-7 engines.* The results for the arrival case are presented in Table 4-2, and the results for the departure case are presented in Table 4-3. The arrival case, which is simpler because gross weight is not a factor, is discussed first.

For an arrival, it is assumed that the fuel saving begins when the aircraft descends below 10,000 feet MSL at a speed higher than 250 knots and ends when the aircraft reaches 5,000 feet MSL. As indicated by the analysis of the Midnight Romeo procedure, deceleration to a speed of 250 or below is likely to be required by the time 5000 feet is reached in order to make the required

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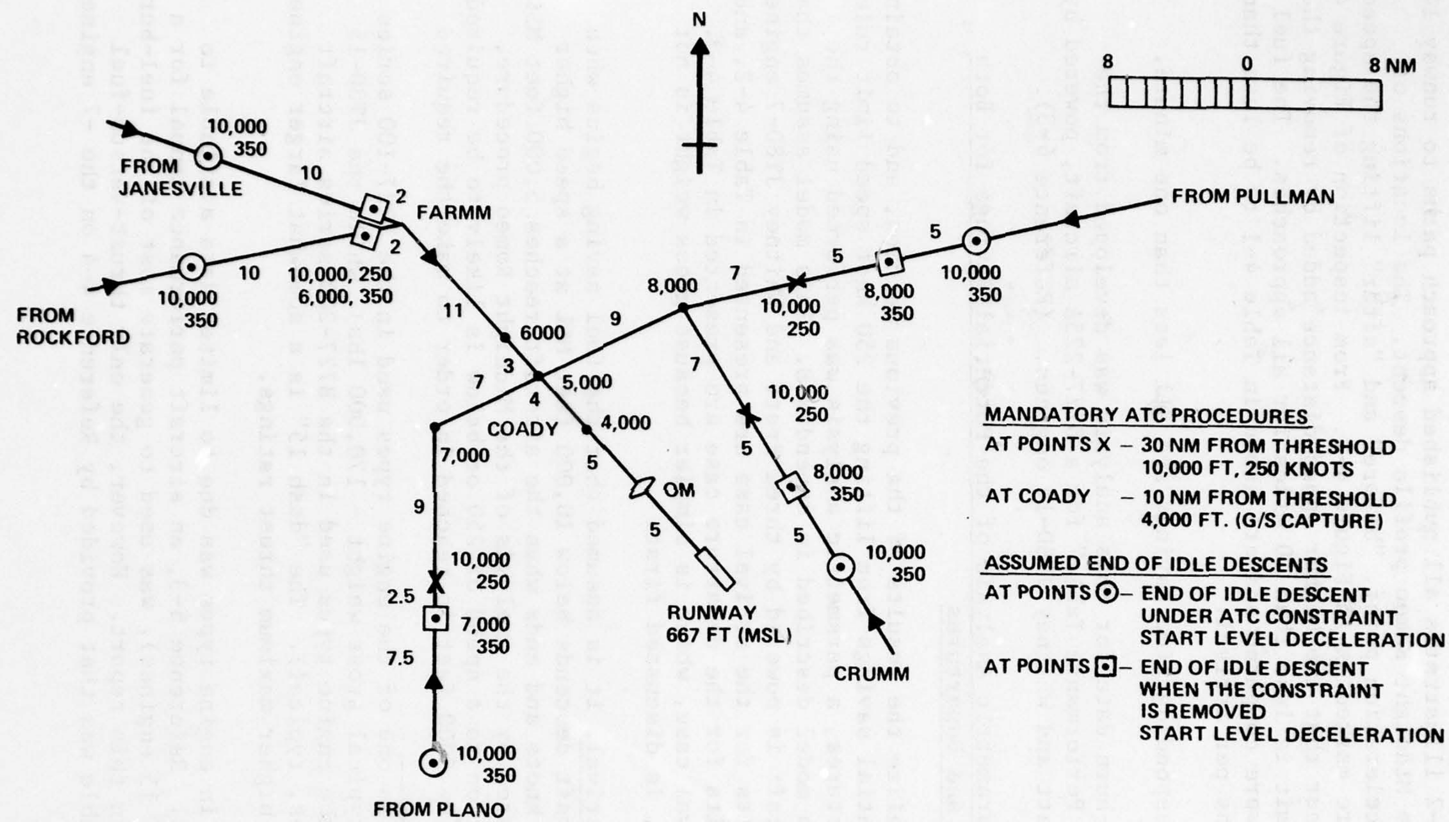
* The JT8D-7 is one of the engine types used in the B727-100 series aircraft (typical gross weight - 170,000 lbs), while the JT8D-15 is one of the engine types used in the B727-200 series aircraft (190,000 lbs. typical). The "dash 15" is a somewhat larger engine with 9-11% higher maximum thrust ratings.

The switch in engine types was due to limited data available to the authors. Reference 6-3, an aircraft performance manual for a B727-225A (-15 engines), was used to generate most of the fuel-burn estimates in this report. However, the only thrust-versus-fuel data available was that provided by Reference 4-4 on the -7 engine



Source: Reference 4-5

FIGURE 4-2
MIDNIGHT ROMEO APPROACH PROCEDURES
TO O'HARE RUNWAY 14R

TABLE 4-1

FUEL SAVINGS WITHOUT THE ATC CONSTRAINT

APPROACH FIX	FINAL ALTITUDE WITH IDLE CLEAN CONFIGURATION (FT)	SAVINGS PER OPERATION		
		TIME (SEC)	FUEL LBS	FUEL GALLONS**
ROCKFORD	6,000	41	50*	7.5
JANESVILLE	6,000	38	60*	9.0
PLANO	7,000	25	50	7.5
PULLMAN	8,000	18	40	6.0
CRUMM	8,000	18	40	6.0

* THE DIFFERENCE IN FUEL SAVINGS IS DUE TO THE EXTRA FUEL REQUIRED IN MAKING A LARGER TURN FROM ROCKFORD APPROACH ROUTE INTO FINAL THAN THE TURN FROM THE JANESVILLE APPROACH ROUTE.

** AT 6.7 LBS/GALLON

TABLE 4-2

FUEL SAVINGS FOR AIRCRAFT DESCENDING FROM 10,000 FT TO 5,000 FT WHEN THE ATC CONSTRAINT OF 250 KNOTS BELOW 10,000 FT IS LIFTED

IAS (KNCTS)	TIME (SECONDS)	DISTANCE (NMI)	FUEL (LBS)	FUEL SAVINGS		
				(LBS)	GALLONS*	%
250	210	16.34	143	0 (REFERENCE)		
280	183	15.88	124	19	2.84	13.29
300	168	15.68	114	29	4.33	20.28
320	156	15.52	106	37	5.37	25.87
350	141	15.30	95	48	7.16	33.57
370	132	15.17	89	54	8.06	37.76
390	124	15.03	84	59	8.80	41.26

*6.7 LBS/GALLON

TABLE 4-3
FUEL SAVINGS FOR AIRCRAFT CLIMBING FROM 3,000 FT TO 10,000 FT (ISA) WHEN THE ATC CONSTRAINT OF 250 KNOTS BELOW 10,000 FT IS LIFTED

WEIGHT (LBS)	IAS (KNOTS)	TIME (SECONDS)	DISTANCE (NMI)	FUEL (LBS)	FUEL SAVINGS		
					(LBS)	(GALLONS*)	%
120,000	250	104	8.00	550	0	(REFERENCE)	
	280	95	8.20	516	34	5.07	6.18
	300	91	8.35	497	53	7.91	9.64
	320	86	8.50	481	69	10.30	12.55
	340	83	8.66	467	83	12.39	15.09
145,000	250	136	10.44	721	0	(REFERENCE)	
	280	125	10.74	676	45	6.72	6.24
	300	119	10.95	651	70	10.45	9.70
	320	114	11.15	630	91	13.58	12.62
	340	109	11.36	612	109	16.27	15.12
160,000	250	158	12.13	837	0	(REFERENCE)	
	280	145	12.49	786	51	7.61	6.10
	300	138	12.73	757	80	11.94	9.56
	320	132	12.96	733	104	15.52	12.43
	340	127	13.21	712	125	18.66	14.93
180,000	250	192	14.69	1013	0	(REFERENCE)	
	280	176	15.13	951	62	9.25	6.12
	300	168	15.43	918	95	14.18	9.38
	320	160	15.73	889	124	18.50	12.24
	340	154	16.02	863	150	22.39	14.80

*AT 6.7 LBS/GALLON

turns. With any traffic at all, slower speeds will almost certainly be required at and below 5,000 feet for sequencing and spacing. Since the time and fuel spent while decelerating from the higher speed, say 320 knots, to 250 knots is about the same at 5,000 feet as it is at 10,000 feet, the fuel and time savings due to the higher speed descent between those two altitudes can be found directly by differencing the fuel burns and elapsed times shown in Table 4-2. For example, the savings due to a 320 knot descent versus a 250 knot descent between 10,000 and 5,000 feet is:

	Fuel	Time
@250 knots	143 lbs.	210 sec.
@320 knots	106	156
	37 lbs.	54 sec.
	(5.4 gallons)	

In general, the most that can be saved per arrival is less than 10 gallons in a B727 with -7 engines. This compares with the less than 10 gallons found to be saved in the Midnight Romeo analysis with -9 engines, when the saving terminated before reaching 5,000 feet.

For a departure, it is assumed that the fuel saving begins when the aircraft reaches 3,000 feet MSL, having accelerated to a speed higher than 250 knots, and ends when the aircraft reaches 10,000 feet MSL. In the departure case, gross weight makes a difference so incremental increases of gross weight from 120 Klbs and 180 Klbs were considered. Assuming that the fuel and time required to accelerate from 250 knots to 320 knots at 3,000 feet is about the same as that required at 10,000 feet, the fuel and time saving can be found directly by differencing the values found in Table 4-3. For example, the savings due to a 320 knot climbout versus a 250 knot climbout between 3,000 and 10,000 feet, given a gross weight of 160 Klbs, is:

	Fuel	Time
@250 knots	837 lbs.	158 sec.
@320 knots	733	132
	104 lbs.	26 sec.
	(15.3 gallons)	

In general, the fuel saving for a departure ranges between 10 and 20 gallons, depending upon the speed differential and gross weight.

It is interesting to note that the percent saving is essentially constant across all gross weights for a given speed differential. For example, if the climb is made at 320 knots, instead of 250 knots, the fuel benefit is about 12% of the fuel burn for that particular climb segment, over the gross weight range of 120 to 180 thousand pounds.

In conclusion, the fuel saving, from lifting the 250 knot speed limit for departures is about three times larger than it is for arrivals. However, in terms of the number of gallons saved, the time and fuel savings are small because the interval over which the speed differential has any effect is small (1.5 to 3.5 minutes), given turbojets that are transitioning unrestricted to/from altitudes above 10,000 feet.

4.2.3 Effects of Traffic on Net Savings

When the effect of traffic are considered, the ability to realize the potential savings can be limited, even if "see and be seen" speed constraints are assumed to be made unnecessary by Stage III radar procedures for the purposes of separation.

In the case of arrivals, reduction to speeds of 210 knots or less for sequencing and spacing to the runway can be expected even with Stage III procedures. Such reductions are typically imposed by the time the aircraft has reached the downwind leg of the runway. Thus, any savings will likely be terminated by the time the aircraft reaches 5,000 feet AGL, even if it is on a straight-in approach. Further, if landing delays are being experienced, any potential time savings due to the higher speeds will not be realized since the delay must be absorbed by a speed reduction or by some other fuel and time-consuming means.

In the case of departures, many terminals have provided climbout paths that are procedurally kept clear of other traffic. To the extend that this remains true, the savings to departures can remain unaffected by the presence of other traffic. Otherwise, the realization of any savings will be limited to the extent that speed or altitude control is required to insure radar separation.

4.3 Estimation of the Potential Annual Fuel Savings

To form an estimate of the savings which might be achieved annually in gallons, the previous results suggest that the average regular-body turbojet would save about five gallons upon arriving at a TCA assuming no landing delay, and save another 15 gallons upon departing that TCA. In the worst case, landing delay would always preclude realizing the arrival savings. Thus, a range of 15 to

20 gallons for each TCA arrival/departure operation by a turbojet could be expected. According to the estimation procedure of Appendix C, the annual number of turbojet TCA operations is 2.4 million, of which only 0.9 million do not require some landing time adjustment for sequencing and spacing:

		Millions Of Gallons Saved Annually
15 gals per departure x 2.4M TCA departures	=	36
5 gals per arrival x 0.9M undelayed TCA arrivals	=	4
		40

5. INCREASE THE NUMBER OF USABLE FLIGHT LEVELS ABOVE 29,000 FEET

To account for decreasing altimeter accuracy with increasing altitude, the current vertical separation standard increases from 1,000 feet below Flight Level 290 (FL290) to 2,000 feet above FL290. Consequently, between FL290 and FL410 and for a given direction of flight, the altitude increment between adjacent usable flight levels is 4,000 feet, and the number of proper direction levels is limited to three:

East to West	West to East
FL390	--
--	FL370
FL350	--
--	FL330
FL310	--
--	FL290

However, from the standpoint of fuel conservation, the optimum cruise altitude for a particular turbojet transport on a medium or long-haul flight* is a function of its gross weight and the outside air temperature.** Since for any given trip, the payload and temperature can vary over wide ranges, and the gross weight can change significantly as fuel burns off, the optimum cruise altitude may lie anywhere between FL290 and FL390. Thus, a fuel penalty is extracted by having to cruise at only one of three discrete flight levels, each separated by 4,000 feet. Increasing the number of flight levels by reducing the vertical separation standard between adjacent flight levels has been suggested as a way of conserving fuel. For example, in 1973, the Air Transport Association petitioned the FAA to reduce the required vertical separation to 1,000 feet up to FL450 by requiring improved altimetry on all aircraft operating above

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* In this study, medium and long-haul flights are assumed to be all flights with stage lengths in excess of 400 nmi.

** That such an optimum exists is clearly illustrated in Figure 2-7.

FL290. Although this particular petition was denied, the value of the potential savings of adding more flight levels remains an unanswered question.*

The purpose of this chapter is to identify and estimate the potential fuel savings of adding more flight levels and to put these savings into perspective relative to the other approaches to fuel conservation considered by this report.

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* According to Reference 5-1, the ATA petitioned the FAA (by letter on 25 April 1973) to reduce the vertical separation between FL290 and FL450 to 1,000 feet. Fuel savings were the expected benefit, but no estimate of the size of the expected savings was provided. However, in order to make the reduction, ATA believed that the following requirements would have to be met by each aircraft using this airspace:

1. A total altimetry system error (instrument error plus static system error) within $\pm$ 250 feet (3σ). (Automatic means to correct altimetry system errors might be required.)

2. Flights at their assigned altitudes would have to use autopilot "altitude hold" above FL290, except in turbulence or given a malfunction.

3. A maintenance program for each operator to assure the required altimetry system accuracy would have to be established.

On 1 March 1977, the FAA denied the petition, after discussions with representatives for the Department of Defense, the Air Line Pilots Association, and the National Business Aircraft Association developed "substantive objections". The objections basically challenged the achievability of ATA's stated requirements. Such factors as the inability of existing aircraft systems or maintenance programs to meet the accuracy requirements, and the operational inability to consistently employ automatic altitude hold devices during cruise, were cited.

The Office of Systems Engineering Management is continuing to investigate this question. Planning for a data collection effort is underway to determine the altitude-keeping accuracy of high altitude flights in level cruise. Distributions of the differences between the assigned and actual altitudes flown would be obtained using precise altitude-measuring radars now located within the United States.

5.1 Potential Fuel Savings Identified

A somewhat more conservative approach than the ATA proposal would be to increase the number of usable flight levels each way from FL290 and FL390 from three to four. Two alternatives have been suggested and are illustrated in Figure 5-1:

1. Reduce the separation standard from 2,000 feet to 1,500 feet between FL290 and FL390 (or, more precisely, FL395).

2. Raise the last usable flight level with 1,000 feet separation from FL290 to FL330, thus adding FL300 and FL320 to the list of usable levels.

If achievable, then the following fuel savings could be obtained:

1. The maximum differential would be reduced between the fuel-optimal altitude and the nearest right-way flight level, thus reducing the average fuel penalty to all flights flying the nearest discrete flight level.

2. Fully-loaded aircraft could make step-climbs somewhat sooner: Since the altitude step for flight in a given direction would be reduced, pilots would be able to request step-climbs sooner as fuel weight burns off.

3. Aircraft vertically avoiding turbulence, or being vertically separated from traffic, at the optimum altitude, could be assigned to an available flight level closer to the currently unavailable optimum altitude (best flight level).

5.2 Estimating the Value of the Potential Fuel Savings on a Per-Flight Basis

According to Reference 5-2, the fuel mileage penalty for cruising at other than the optimum altitude is for all Boeing aircraft:

	Fuel Mileage Penalty-Percent	
	At LRC	At Constant Mach
2000 Feet Above	1%	2%
Optimum Altitude	0	0
2000 Feet Below	1	2
4000 Feet Below	2	4
8000 Feet Below	8	12

FIGURE 5-1

ALTERNATIVES FOR FLIGHT LEVELS BETWEEN FL290 AND FL410

	WITH CURRENT 2000' SEPARATION		WITH 1000' EXTENDED TO FL330		WITH 1500' SEPARATION	
	EAST-WEST	WEST-EAST	EAST-WEST	WEST-EAST	EAST-WEST	WEST-EAST
410						
					FL395	
390	FL390		FL390			
						FL380
370		FL370		FL370		
					FL365	
350	FL350		FL350			FL350
					FL335	
330		FL330		FL330		
			FL320			FL320
310	FL310			FL310		
					FL305	
			FL300			
290		FL290		FL290		FL290
270						

VERTICAL SEPARATIONS REMAIN AT 1000' BELOW FL290

Flying higher than 2,000 feet above the optimum altitude for the aircraft's current gross weight is not recommended by Boeing.

For example, a B727-200 Klbs. gross weight flies optimally at FL290, while burning about 4,000 lbs. of fuel per hour per engine. At a gross weight of 175 Klbs., the aircraft flies optimally at FL330, while burning about 3,500 lbs. per hour per engine. Assume that the aircraft climbs to an initial cruise altitude of FL290 while weighing 200 Klbs. Its optimal cruise altitude will gradually rise as fuel is burned off, passing FL330 after little more than two hours into the cruise segment.

Since the airlines have not in the past maintained records on fuel losses due to flying non-optimum altitudes, it is necessary to rely on a theoretical estimate for both what these losses have been and what fuel savings might accrue by changing from the present three flight-level structure to either of the alternate four flight-level structures. In building such an estimate, two alternative assumptions can be made:

1. Traffic competition for the fuel optimum flight level is not a factor. Each turbojet aircraft in level cruise at or above FL290 will be operated at LRC speed and at the flight level nearest the fuel-optimum altitude for its current gross weight. The potential fuel saving would accrue solely from the reduction in spacing between adjacent flight levels, thus minimizing the maximum possible difference between the assigned altitude and the fuel-optimum altitude.

2. Traffic competition for the fuel optimum flight level is a factor. Flights requesting a higher flight level cannot be assigned that flight level when requested, due to traffic above. Such flights pay a fuel penalty which grows non-linearly with time when forced to remain at the lower non-optimum cruise altitude. Adding one additional flight level each way might relieve some of this competition and thus produce additional fuel savings.

For example, if the current vertical separation standard of 2,000 feet is assumed, then under assumption 1, FL330 will be the fuel-optimum flight level flown by all east bound flights whose optimum fuel altitude lies between 31 and 35 thousand feet. However, under assumption 2, some of the flights assigned FL330 would, on occasion, cause others to remain at FL290. In the former case, all aircraft are operated within 2 thousand

feet of their fuel optimal altitude. In the latter case, some operate between 4 and 6 thousand feet below their fuel optimal altitude, while the rest operate within 2 thousand feet.

The analysis which follows is based solely on the first assumption and thus may be somewhat conservative. However, in the author's opinion, it represents the truer state of affairs. That is, assignment to a cruise altitude other than requested for any length of time is the exception, rather than the rule. Such cases do occur, but these are usually due to procedural restrictions which segregate traffic which is transitioning in altitude--see Chapter 6. In such cases, just adding more flight levels will be insufficient to realize the potential fuel savings.

Based on assumption 1 above, and using the procedure described in Appendix D.1, the average fuel benefit on a per-flight basis is computed to be:

Flight Levels Each Way	Vertical Separation Standard		Expected Fuel Penalty (f)	
3	2000' (FL290-390)		1.0%	
4	1500' (FL290-390)	0.25% Saving	0.7%	0.5% Saving
4	1000' (FL290-330)		0.5%	

That is, the expected (mean) fuel saving resulting from the 1,500 foot standard up to FL390 is 0.25% of the total cruise burn for any medium or long-haul flight operating at its best flight level between FL290 and FL390. Similarily, the expected (mean) fuel savings resulting from the 1,000 foot standard up to FL330 is 0.5% of the total cruise burn for any medium or long-haul flight operating at its best flight level between FL290 and FL330.

These percent savings per flight can be converted to an estimated per flight savings in gallons using the results of Appendix C.2. The weighted average savings for all flights, regular-body and wide-body, cruising at their fuel-optimal flight levels and speeds between FL290 and FL390, and using the 1,500 foot spacing, is 6.3 gallons per flight. Similarily, the weighted average savings for the heavier flights only, regular-body and wide-body, cruising at their fuel-optimal flight levels and speeds between FL290 and FL330, and using the 1,000 foot spacing, is 11.0 gallons per flight. The assumptions and data used to compute these estimates are summarized in the next section.

Some Additional Observations:

Referring to Figure 2-7, it can be seen that the fuel penalty per mile is small for a B727-200 operating within two thousand feet of its fuel-optimal altitude. But when the aircraft operates 4,000 feet or more away from its optimum altitude, then the non-linearity of these curves is pronounced, and the penalty becomes significant. This explains why the fuel benefits are small if traffic is not a factor, but could be larger if competing traffic denies the use of the best level.

Comparing the analysis in Appendix D.1 with Figure 2-7, it can be seen that the curves in the figure are plotted examples of the fuel burn function "$F_o + dF$" used in the analysis. In that analysis, the function x(z) is used to integrate the percent of excess fuel burned over the range of possible altitude differences between the optimal altitude and the nearest available right-way flight level. Comparing it to Figure 2-7, x(z) can be seen as a linear approximation of that portion of the curves between 0 and 2 thousand feet. However, the source data for x(z) is said to be applicable to all Boeing aircraft, and not just the B727-200. Therefore, the results of this analysis are more generally applicable.

5.3 Estimating the Potential Annual Fuel Savings

To estimate the potential annual savings (in gallons) from the per-flight savings above, the procedure and data described in Appendix D.2 were used. Since the percent fuel savings were computed relative to fuel-optimal flight, all medium and long-haul flights were assumed to be operating at their fuel optimum altitudes and speeds (LRC) for their current gross weight. Using the B727-200 as the representative regular-body aircraft and the L-1011 as the representative wide-body aircraft, the average of the fuel flows per nmi for all flight levels of interest for each aircraft type were computed. These flows were applied to the average cruise distances estimated for regular-body and wide-body aircraft, yielding the minimum fuel burn averages per flight shown in Table 5-1.

Estimates of the average number of such flights daily were then made, applied to the individual flight burns, and multiplied by 365. The potential annual fuel savings, in gallons, were computed using the percent savings found previously. These results are also shown in Table 5-1.

AD-A059 050 MITRE CORP MCLEAN VA METREK DIV F/G 21/5
ATC ACCOMODATION OF FUEL CONSERVATIVE TURBOJET OPERATIONS.(U)
MAY 78 S C MOHLEJI, R A RUCKER, B M HOROWITZ DOT-FA78WA-4075
UNCLASSIFIED MTR-7849 FAA-EM-78-14 NL

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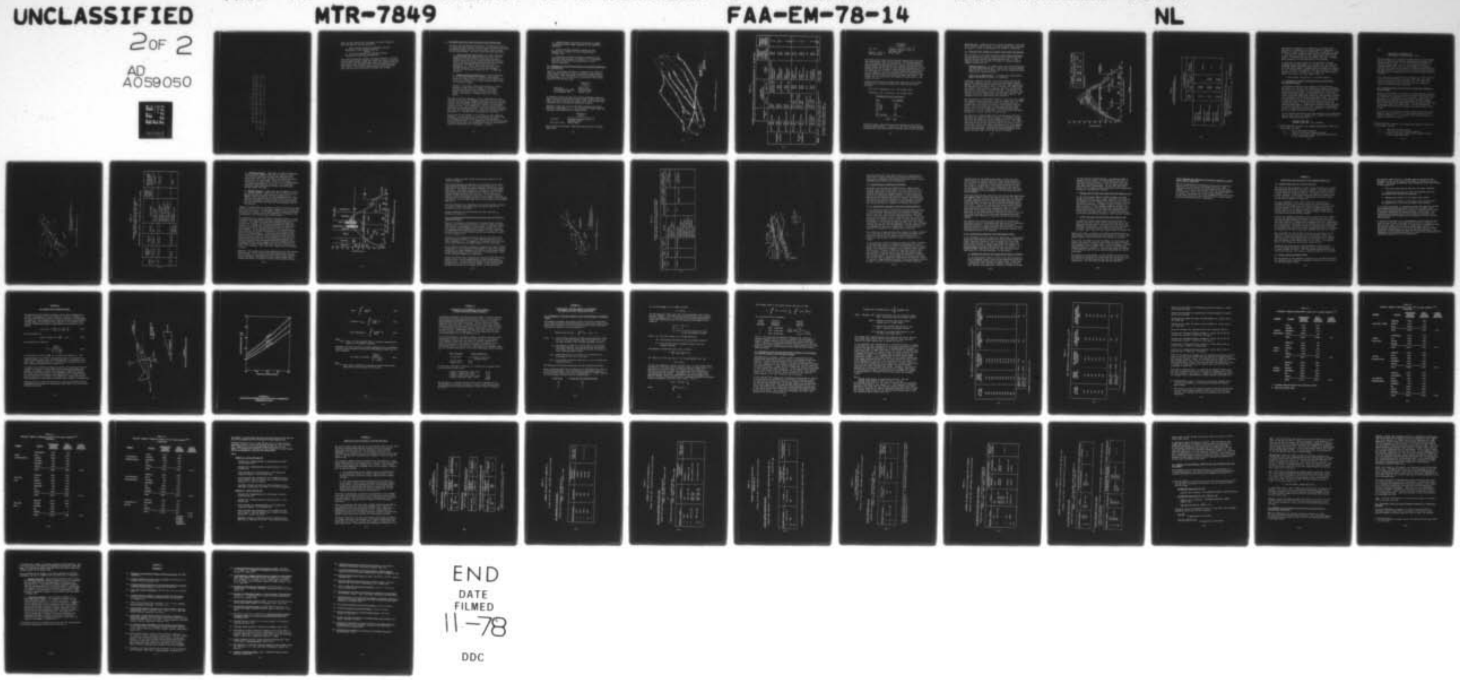

END
DATE
FILMED
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TABLE [illegible]

[illegible]

	ESTIMATED PERCENT EXCESS FUEL PER AVERAGE FLIGHT [illegible]	ESTIMATED MINIMUM FUEL PER AVERAGE FLIGHT (IN GALLONS)	ESTIMATED NUMBER OF DAILY FLIGHTS OVER 500 NM	FUEL SAVINGS PER AVERAGE FLIGHT (GALLONS)	ESTIMATED ANNUAL SAVINGS (IN MILLIONS OF GALLONS)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	[illegible]	16.5	
			[illegible]	Weighted Avg: [illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	11.0	10
		[illegible]	[illegible]	[illegible]	
			[illegible]	Weighted Avg: [illegible]	

* [illegible]

These results indicate that the amount of annual savings is about the same for either *alternative:*

1. Twelve million gallons if 1,500 feet vertical separation is used between FL290-390

versus

2. Ten million gallons if 1,000 feet vertical separation is used between FL290-330.

The second alternative provides the greater benefit to the more heavily loaded flights (those that cannot yet operate optimally above FL330), but that advantage is more than offset by the fact that these flights represent only 37% of all medium and long-haul flights. The majority operate between FL330 and FL390 where the only first alternative provides fuel savings.

6. ELIMINATE FIXED CRUISE AND CROSSING ALTITUDE RESTRICTIONS

To assure safe and expeditious movement of turbojet aircraft in the busier airspace regions, ATC has frequently found it necessary to segregate potentially conflicting traffic flows by fixed altitude restrictions. Two basic types have been identified:

1. Cruise altitude restrictions for flights with stage lengths between city pairs of less than, say, 250 nmi. Examples of cruise altitude restrictions are those imposed during the day for flights between New York and Boston, New York and Washington, New York and Pittsburg, and between Philadelphia and either New York or Washington, D.C. These restrictions basically limit turbojet operations to the low altitude structure (17,000 feet and below) between the hours of 0600 and 2200 EST.

2. Crossing altitude restrictions at center boundaries or at busy intersections for flights transitioning between the high altitude structure and a terminal area. These often become de facto cruise altitude restrictions for short-haul flights.

   Examples of altitude crossing restrictions at a center boundary include those for flights from Chicago to Cleveland (cross the center boundary at/or below FL240), from Dayton to Chicago (cross at/or below FL220), from Detroit to Chicago (cross at/or below FL220).

The size of the fuel penalties, if any, resulting from such altitude restrictions are dependent upon many factors, including aircraft type and weight, flight stage length, and the type and location of the altitude restriction relative to the desired altitude profile. Thus estimation of the fuel penalty must be conducted on a case-by-case basis. Only one case, that involving the cruise altitude restrictions on short-haul flights between Washington, D.C. and New York, is analyzed by this study.

The purpose of this chapter is to estimate the fuel penalties imposed by a particular set of cruise altitude restrictions and to investigate the traffic factors which have made these restrictions necessary. It is argued that the problems found might be solved without the use of fixed restrictions if an additional controller automation aid is developed. It would:

1. compute whether an altitude restriction is needed for each short-haul flight, based on actual predicted conflicts,

2. resolve overtake situations between aircraft merging onto a common route and transitioning in altitude, and

3. provide the necessary clearance coordination data when more than one sector is involved. It is believed that such an aid would have application in other similar situations.

6.1 Background on High Altitude Restrictions Between Washington, D.C. and New York

Figure 6-1 illustrates and Table 6-1 summarizes the preferred route structure and the altitude restrictions which existed as of May, 1976. There were three low altitude preferred routes from Washington, D.C. to New York, one for each of the primary airports in the New York area:

	Destination Airport
V433.Harry	Newark (EWR)
V123.Robbinsville (RBV)	LaGuardia (LGA)
V44.Southgate (7XG)	Kennedy (JFK)

The departures bound for New York from all Washington area airports go out over the departure fixes listed, merge at Swan Point (7NP), and then divide as each connects with the preferred route associated with its particular destination airport.

Similarly, there were five low altitude preferred routes from New York to Washington, D. C. Two routes serve Newark (EWR) and LaGuardia (LGA) departures via Solberg (SBJ):

	Destination Airport
V3..V378	Washington National (DCA), or Baltimore (BAL)
V30..V39..V143S	Dulles (IAD)

Three routes serve Kennedy (JFK) departures bound for the Washington area:

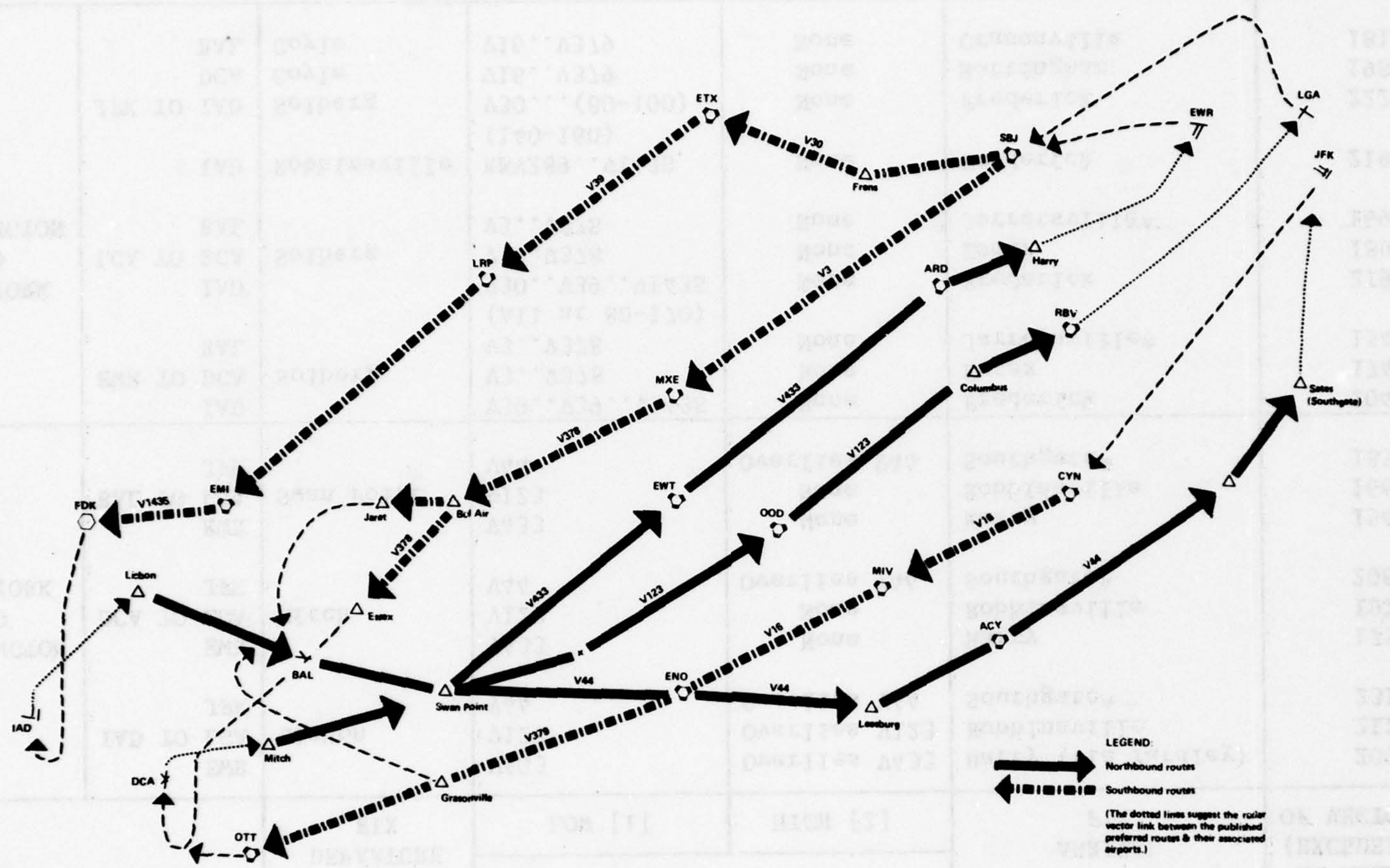


FIGURE 6-1
PREFERRED LOW ALTITUDE ROUTE STRUCTURE BETWEEN WASHINGTON, D.C. AND NEW YORK

TABLE 6-1

PREFERRED ROUTE STRUCTURE AND UTILIZATION BETWEEN WASHINGTON, D.C. AND NEW YORK

		Departure Fix	Published Preferred Route: Low [1]	Published Preferred Route: High [2]	Arrival Fix	Approximate Route Distance N. Miles (Exclusive of Vectoring)	Number of Weekday Flights (Turbojet Nonstop)
WASHINGTON TO NEW YORK	IAD TO EWR	Lisbon	V433	Overlies V433	Harry (Via Yardley)	200	6
	IAD TO LGA	Lisbon	V123	Overlies V123	Robbinsville	212	6
	IAD TO JFK	Lisbon	V44	Overlies V44	Southgate*	231	11
	DCA TO EWR	Mitch	V433	None	Harry	175	10
	DCA TO LGA	Mitch	V123	None	Robbinsville	187	23
	DCA TO JFK	Mitch	V44	Overlies V44	Southgate*	206	5
	BAL TO EWR	Swan Point	V433	None	Harry	154	2
	BAL TO LGA	Swan Point	V123	None	Robbinsville	166	4
	BAL TO JFK	Swan Point	V44	Overlies V44	Southgate*	185	8
							75
NEW YORK TO WASHINGTON	EWR TO IAD	Solberg	V30..V39..V143S	None	Frederick	204	5
	EWR TO DCA	Solberg	V3..V378	None	Essex	174	9
	EWR TO BAL	Solberg	V3..V378 (All at 80-170)	None	Jarretsville*	154	1
	LGA TO IAD	Solberg	V30..V39..V143S	None	Frederick	219	6
	LGA TO DCA	Solberg	V3..V378	None	Essex	189	22
	LGA TO BAL	Solberg	V3..V378	None	Jarretsville*	169	3
	IAD	Robbinsville	RBV289..V143S (140-160)	None	Frederick	219	7
	JFK TO IAD	Solberg	V30...(80-100)	None	Frederick	222	6
	JFK TO DCA	Coyle	V16..V379	None	Nottingham	198	5
	JFK TO BAL	Coyle	V16..V379	None	Crasonville	181	5
							69
						192 AVG	144

NOTES: Sources: AIM, Part 3, March 1976 (Reference 6-1)
OAG, May 1976 (Reference 6-2)

* NOW "SATES"
** NOW "JARET"

[1] 90-170 unless otherwise noted
[2] "none" between 0700 and 2300 EDT

	Destination Airport
V16..V379	Washington National (DCA), or Baltimore (BAL)
RBV289...V143S, or V30..V39..V143S	Dulles (IAD)

Note that all but three of the preferred routes listed in do not have complimentary high altitude routes. The three exceptions are the two high routes that overlie the low altitude preferred routes between IAD and the New York airports, and the high route which overlies the off-coastline low altitude preferred route from DCA/BAL to JFK via Southgate. High altitude preferred routes are not published for the other city pairs because ATC procedurally will not normally clear short-haul aircraft into these altitudes between 0700 in the morning and 2300 at night (EDT, daily). The reasons for this restriction are examined in some detail in subsequent sections.

Analysis of the Official Airline Guide (Reference 6.2) revealed the following scheduled utilization of these routes by the airlines:

New York to Washington, D.C. = 128 flights daily

Washington, D.C. to New York = 155 flights daily

EQUIPMENT MIX (Both Directions):

Type	% of Flights	
DC9-S	34	71%
727-100	24	
727-200	13	
707-320	3	
737		
747	<1	
Not Turbojet	25%	
TOTAL	100%	

Of these flights, 144 were found to be turbojet non-stop flights operating every weekday. Of these 144, 108 (75%) operated between Washington-New York airport pairs connected only by a low altitude

preferred route. Based on the then current procedures, these 108 daily flights could not expect to obtain assigned cruise altitudes in excess of 17,000' if northbound, and 16,000' if southbound.

6.2 Potential Fuel Savings on a Single Flight Basis and Annually

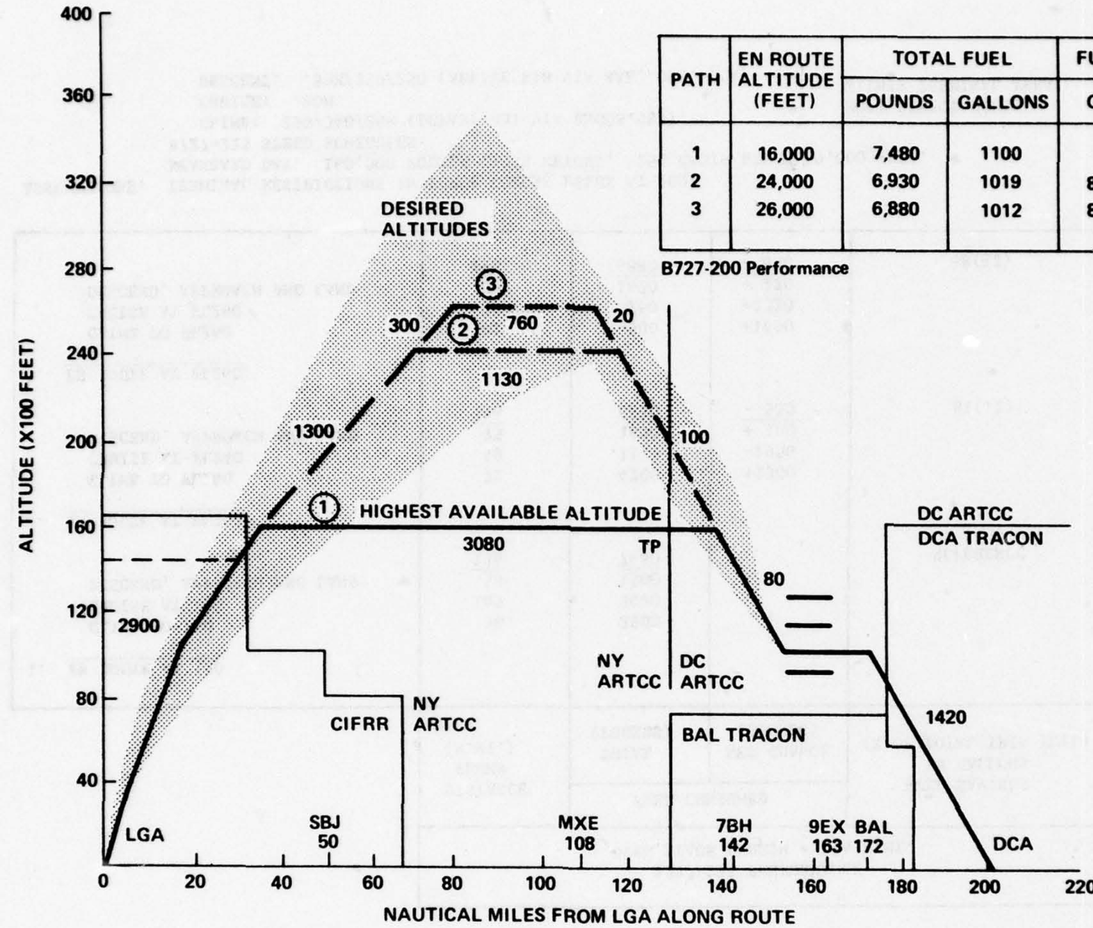
The two busiest low altitude preferred routes between Washington, D.C. and New York are those on which Eastern's shuttle aircraft operate between LaGuardia and Washington National. If only turbojet aircraft are counted, the number of scheduled weekday flights on each route is:

> Solberg to Bel Air: 35 flights daily from LGA-to-DCA/BAL(25) and from EWR-to-DCA/BAL(10). From Bel Air, aircraft landing National DCA arrive via Essex, and aircraft landing Baltimore (BAL) arrive via Jarrettsville.
>
> Swan Point to Robbinsville: 33 flights daily from DCA(23), BAL(4), and Dulles or IAD(6), to LaGuardia.

According to Eastern Airlines, the optimal cruise altitude for their DC9s operating from LGA to DCA is either FL240 or FL260. However, the New York ARTCC typically will not grant higher than 160 (altitude in hundreds of feet). Similarly, for their DCA to LGA flights, FL250 to FL270 is optimal, but these are typically restricted to altitude 170 (17,000 feet MSL). According to the analysis in the previous section, it would appear that about 108 turbojet short-haul flights daily are similarly affected. The equipment types are predominately DC9s and B727s.

This situation is illustrated in Figure 6-2 for LGA to DCA flights. The highest available altitude is 160, but either FL240, or FL260 is preferred. The shaded area bounds the standard day fuel-optimal climb and descent profiles for light-to-heavy DC9s and B727s. The figure shows that LGA departures normally climb unrestricted to their assigned cruise altitudes and normally descend so as to cross Essex (9EX), level at altitude 100 unless holding is in effect, in order to land at DCA.

The benefits of being assigned one of the more fuel efficient altitudes were computed, and the results are tabulated in both Table 6-2 and Figure 6-2, using available fuel burn and flight time data for a B727-225A aircraft (Reference 6-3). The results show that between 80 and 90 gallons can be saved over a total trip length of about 200 miles, representing a 7% to 8% savings in the total fuel burn. Assuming the more conservative FL240 versus 160 improvement, the 81 gallon savings translates into $28.35 saved per trip, if 35¢ per gallon is assumed.



PATH	EN ROUTE ALTITUDE (FEET)	TOTAL FUEL		FUEL SAVINGS	
		POUNDS	GALLONS	GALLONS	%
1	16,000	7,480	1100	baseline	
2	24,000	6,930	1019	81	7
3	26,000	6,880	1012	88	8

B727-200 Performance

FIGURE 6-2
DESIRED VERSUS AVAILABLE ALTITUDES FOR LaGUARDIA-TO-NATIONAL FLIGHTS

TABLE 6-2

FUEL BENEFITS OF HIGHER ALTITUDE
ASSIGNMENTS FOR LAGUARDIA-TO-NATIONAL FLIGHTS

	B727-225 PERFORMANCE OVER STAGE LENGTH = 196 N.Mi.			
	DISTANCE FLOWN (N.Mi.)	FUEL CONSUMED TOTAL (POUNDS)	FUEL CONSUMED NET CHANGE (POUNDS)	FUEL SAVINGS IN GALLONS (% OF TOTAL TRIP FUEL)
1. EN ROUTE AT 160				
CLIMB TO 160	36	2900		
CRUISE AT 160	105	3080		
DESCEND, APPROACH AND LAND	55	1500		
	196	7480		REFERENCE
2. EN ROUTE AT FL240				
CLIMB TO FL240	72	4200	+1300	
CRUISE AT FL240	49	1130	-1950	
DESCEND, APPROACH AND LAND	75	1600	+ 100	
	196	6930	- 550	81(7%)
3. EN ROUTE AT FL260				
CLIMB TO FL260	81	4500	+1600	
CRUISE AT FL260	35	760	-2320	
DESCEND, APPROACH AND LAND	80	1620	+ 120	
	196	6880	- 600	88(8%)

ASSUMPTIONS: TERMINAL RESTRICTIONS IN FORCE (CROSS ESSEX AT 100)
STANDARD DAY. 160,000 POUNDS GROSS WEIGHT. 250 KNOTS BELOW 10,000 FEET.
B727-225 SPEED SCHEDULES:
CLIMB: 250/340/80M (DEPART R31 VIA RNG08.SBJ)
CRUISE: .80M
DESCENT: .80M/350/250 (ARRIVE R18 VIA BAL..GTN..DCA)

$\Big\}$ MOST DIRECT ROUTE WITHIN TERMINAL AREA

With regard to flying time, it takes about 13 minutes from departure fix (Solberg) to arrival Fix (Essex), regardless of whether the flight cruises at 16,000 feet, or continues to climb to FL240 or FL260, cruises a short distance, and again descends to cross Essex at 10,000' MSL (the latter takes about 1/2 min. longer). The dollar value of this slight time loss is probably small compared to the estimated $28 in fuel savings.

To annualize the fuel savings for the short-haul turbojets operating between Washington, D.C. and New York, the number of scheduled flights operating along restrictive routes is found to be 108 every weekday. Assuming that the average fuel savings for each operation is 81 gallons, and that the number of flights annually is 108 [5 + 2(80%)] 52, or 37,000, then the potential annual fuel savings for these flights alone is:

37,000 flights x 81 gallons = 3.0 million gallons.

6.3 Assessing the Traffic Problems Solved by Fixed Cruise Altitude Restrictions

A preliminary analysis of the airspace structure between Washington, D.C. and New York showed that a number of published jet routes cross or merge with the published short-haul preferred routes at and above FL180. It was reasonable to assume that if these conflicting routes were loaded with traffic, then the air traffic controller might have a difficult time finding a conflict-free clearance for a short-haul flight above FL180. This would be particularly true if the crossing traffic were transitioning in altitude, thus limiting the controller's ability to use altitude separation. To determine the frequency which such conflicts materialize, a limited data collection effort was made at the New York ARTCC in July, 1976. The data was subsequently reduced and analyzed as described in Appendix E. What follows here is a summary of what was learned.

The two busiest short-haul routes were singled out for observation. Each of these routes was thought of as a single short-haul route without altitude restrictions; i.e.,

<u>Solberg to Bel Air</u> =
LGA/EWR...SBJ..MXE.. BH...DCA/BAL*

* In this and other examples, the standard NAS computer flight plan route format is used:

"."	=	"Route.Fix.Route" connector
".."	=	"Fix..Fix" or "Route..Route" connector
"..."	=	Ellipsis indicating intentionally omitted portions of the flight plan route.

and

Swan Point to Robbinsville =
DCA/BAL/IAD...7NP..OOD..RBV...LGA*

Data was taken on all turbojets observed on each of these routes and on all turbojets potentially interacting with these routes between FL180 and FL290. It was confirmed that turbojets on these short-haul routes were, in fact, being restricted to altitudes below FL180. The type and frequency of potential conflicts that might have occurred, if these short-haul turbojets had been allowed to climb unrestricted to FL240 or FL260 before descending into the Washington, D.C. or New York areas, were also recorded.

Since the period of observation was limited to a single five hour period for the southbound route (SBJ...7BH), and to a single three hour period for the northbound route (7NP...RBV), the following observations and conclusions must be regarded as subject to a more thorough assessment.

6.3.1 Potential High Altitude Conflicts Along the "Solberg to Bel Air" Route

Figure 6-3 illustrates the potential for high altitude conflicts as observed over a five hour period on a semi-busy Friday morning (23 July 1976; see Appendix E.1 for details). During this five hour period, 16 short-haul turbojets were observed to depart LaGuardia (LGA), Newark (EWR), Westchester Co. (White Plains, HPN), or Morristown Muni (MMU) bound for Washington National (DCA) or Baltimore (BAL) via Solberg (SBJ). All were cleared via SBJ.V3.MXE.V378.7BH and were assigned altitudes of 160 or below by ATC.

Statistics on the observed potential conflicts with these short-hauls are shown in Table 6-3. A more detailed analysis can be found in Appendix E-1. To summarize, there were two types of potential conflicts observed:

---

* In this and other examples, the standard NAS computer flight plan route format is used:

"."	=	"Route.Fix.Route" connector
".."	=	"Fix..Fix" or "Route..Route" connector
"..."	=	Ellipsis indicating intentionally omitted portions or the flight plan route.

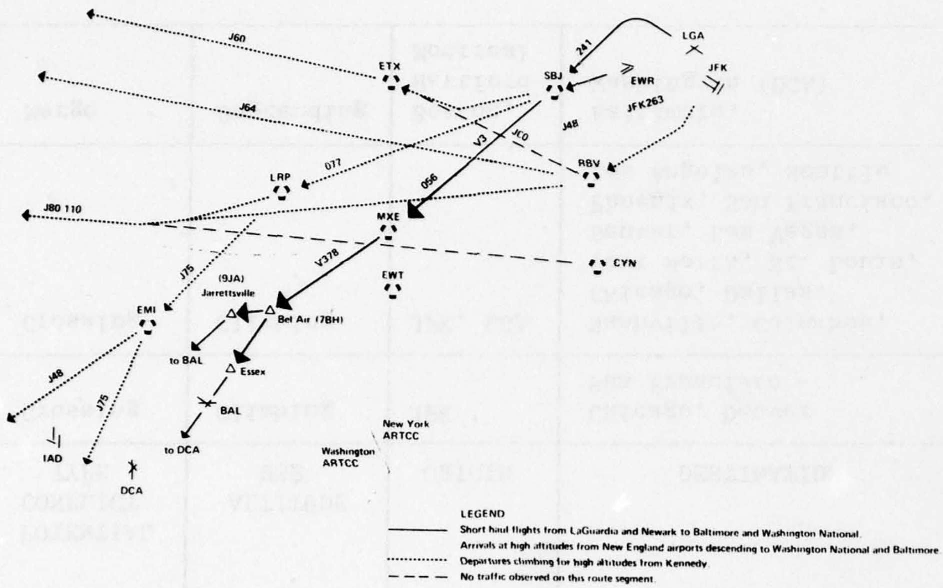


FIGURE 6-3
OBSERVED HIGH ALTITUDE TRAFFIC CROSSING/MERGING WITH THE "SOLBERG TO BEL AIR" ROUTE

TABLE 6-3

OBSERVED POTENTIAL FOR HIGH ALTITUDE CONFLICTS
ALONG THE "SOLBERG TO BEL AIR" ROUTE

Observed During 7:30 am - 12:30 pm EDT, 23 July 1976 (Friday)

ROUTE	POTENTIAL CONFLICT TYPE	ALTITUDE USE	ORIGIN	DESTINATION	OBSERVED FLIGHTS PER HR., AVERAGE	OBSERVED RANGE OF ALTITUDES CROSSING V3
J64	Crossing	Climbing	JFK	Chicago, Denver San Francisco	1	FL200-290
J80	Crossing	Climbing	JFK, LGA	Nashville, Columbus, Chicago, Dallas, Fort Worth, St. Louis, Denver, Las Vegas, Phoenix, San Francisco, Los Angeles, Seattle	4	FL220-300
J48	Merge	Descending	Boston, Hartford Montreal	Baltimore, Washington (DCA)	2	FL220

1. <u>Crossing conflicts</u>: These were the JFK/LGA departures on J64 and J80. Based on the data in Table 6-3, about five New York departures per hour were observed to be using either J64 or J80. Of these, all crossed the short-haul route at or above FL200, but only one in three crossed it at or above FL270. Thus, if this limited sample is assumed representative, about two out of three JFK departures might potentially conflict with short-hauls wanting higher altitudes.

2. <u>Merging conflicts</u>: These were the New England arrivals via J48 for DCA/BAL. Based on the data in Table 6-3, about two arrivals per hour were observed to merge onto the MXE056° radial for descent into the Washington area. These aircraft were observed level at FL220 until after the turn, then were cleared for further descent and in-trial merging with the short-hauls also bound for the Washington area at altitude 160.

Figure 6-4 illustrates this situation in vertical profile and shows why the restriction of the short-haul flights to 170 or below has made sense in the past. Specifically, altitude separation between the short-haul flights and the JFK departures is assured, and the short-hauls do not load any high altitude sector.

The problem with the rigid altitude restriction, however, is that it denies short-hauls higher altitudes even when they are free of conflicts. For example, suppose each crossing JFK departure occupies the airspace over the short-haul route for about two minutes (i.e., assume the intersection width to be protected by ATC is eight miles at 480 knots TAS and a factor of two for convervatism). At the observed average of five departures per hour either on J64 or J80, 50 minutes out of each hour would be free of crossing conflicts. If the worst-case peaking of JFK departures is twice observed, then 40 minutes an hour would be free of crossing conflicts. The 20 minutes per worst-case hour during which either the J64 or J80 intersection would be considered occupied (above some minimum altitude attainable by the occupying aircraft) can be thought of as ten discrete intervals distributed in some random fashion over the hour, relative to a total of 30 intervals. Thus, two out of three times the airspace is clear.

Therefore, one problem to be solved regarding J64 and J80 crossing departures is: How to predict when both intersections will be free of traffic so that unrestricted short-haul cruise altitudes could be assigned? Alternatively, how to predict when either intersection would be occupied, and above what minimum altitude,

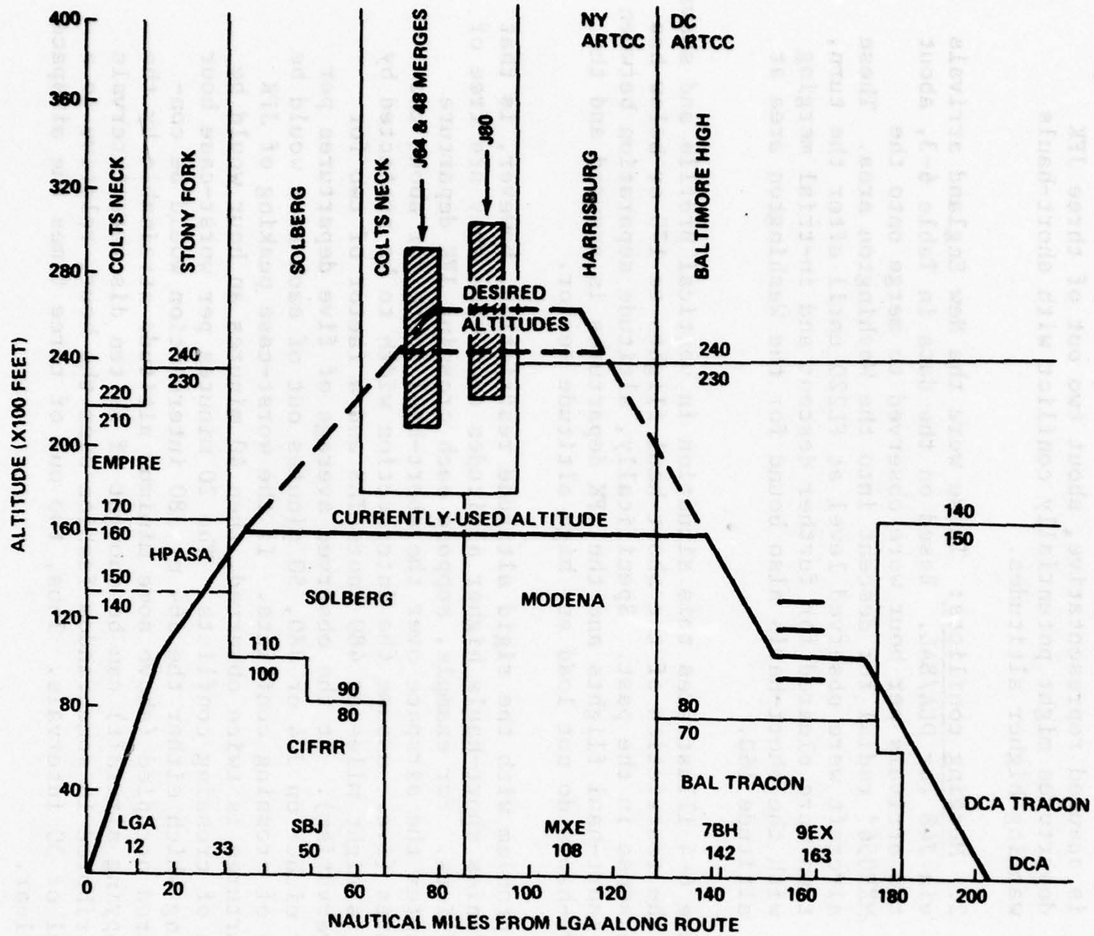


FIGURE 6-4
SECTORIZATION VERTICALLY ALONG THE "SOLBERG TO BEL AIR" ROUTE

so that a lower, but less restrictive altitude than 160 or 170 could be assigned?

The second problem to be addressed is the shifting of the short-hauls to become "handles" for the Colts Neck High sector. At or above FL240, they would also become "handles" for the Harrisburg High sector. According to Table A-1, as many as six short-haul turbojets per hour were observed on the Solberg to Bel Air route, and the average was about three per hour. If the worst-case peaking of these short-hauls is twice the hourly peak observed, then as many as 12 turbojets per hour could be added to the "handles workload" of the Colts Neck High sector, and possibly the Harrisburg High sector.

The third problem to be addressed is the earlier merging at higher altitudes of these short-hauls with the J48 arrivals, if the restriction were to be lifted.

Further discussion of these problems and their solutions is deferred to Section 6.4.

6.3.2 Potential High Altitude Conflicts Along the Swan Point-to-Robbinsville Route

Figure 6-5 illustrates the potential for high altitude conflicts observed over a three hour period on a semi-busy Thursday evening (22 July 1976, see Appendix E.2 for details). During this three hour period, five short-haul turbojets were observed to depart the Washington area northbound for LaGuardia via Swan Point (7NP). All were cleared via 7NP.V123.RBV and all were assigned altitudes of 170 or below by ATC.

Statistics on the observed potential conflicts with these short-hauls are shown in Table 6-4. A more detailed analysis can be found in Appendix E.2. To summarize, all potential conflicts were LGA arrivals which must be merged anyway with the short-hauls.

No new conflict would be introduced by removing the cruise altitude restriction, but it would cause these merges to take place earlier, resulting in a longer common path to RBV over which proper spacing between transitioning aircraft would have to be maintained. This is one potential problem to be addressed.

Unlike the previous case, removing the cruise altitude restriction would not shift control responsibility of these short-hauls to another sector. As illustrated in Figure 6-6, the Woodstown low altitude sector controls the entire length of this route through the New York center and up through FL290. If the short-haul

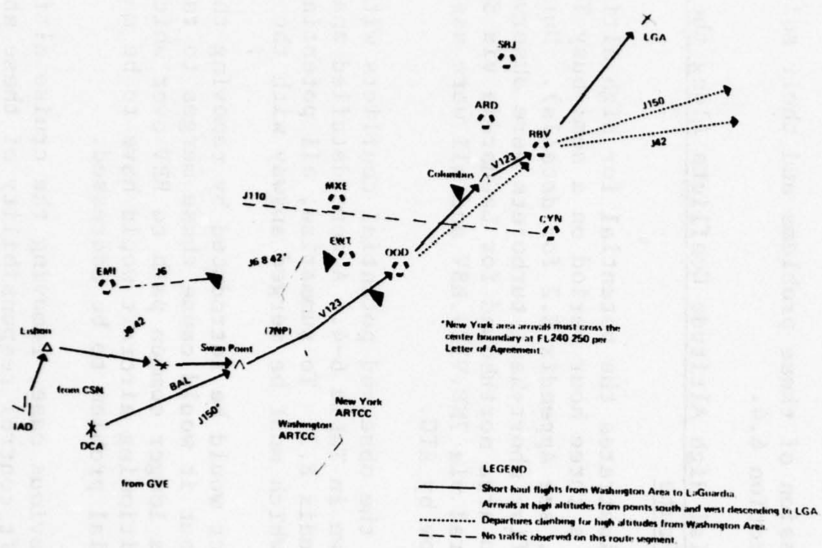


FIGURE 6-5
OBSERVED HIGH ALTITUDE TRAFFIC MERGING WITH THE "SWAN POINT TO ROBBINSVILLE" ROUTE

TABLE 6-4

OBSERVED POTENTIAL FOR HIGH ALTITUDE CONFLICTS
ALONG THE SWAN POINT-TO-ROBBINSVILLE ROUTE

CONFLICTING ROUTE	CONFLICT TYPE	ALTITUDE USE	ORIGIN	DESTINATION	OBSERVED FLIGHTS PER HR., AVERAGE	OBSERVED RANGE OF ALTITUDES (FT.)
J150	Merge	Descending	Palm Beach, Fayetteville, Raleigh - Durham, Miami, Atlanta	LGA	2	FL250-200 at Center Boundary
J6-8-42	Merge	Descending	Greenville, Spartanburg, Greensboro, Memphis Charlottesville, Columbia, Charlotte, Dallas, Fort Worth, Louisville, Knoxville, Atlanta, Nashville, Houston, Lynchburg, New Orleans	LGA	5 (Range: 4 to 8)	FL240-100 at New Castle

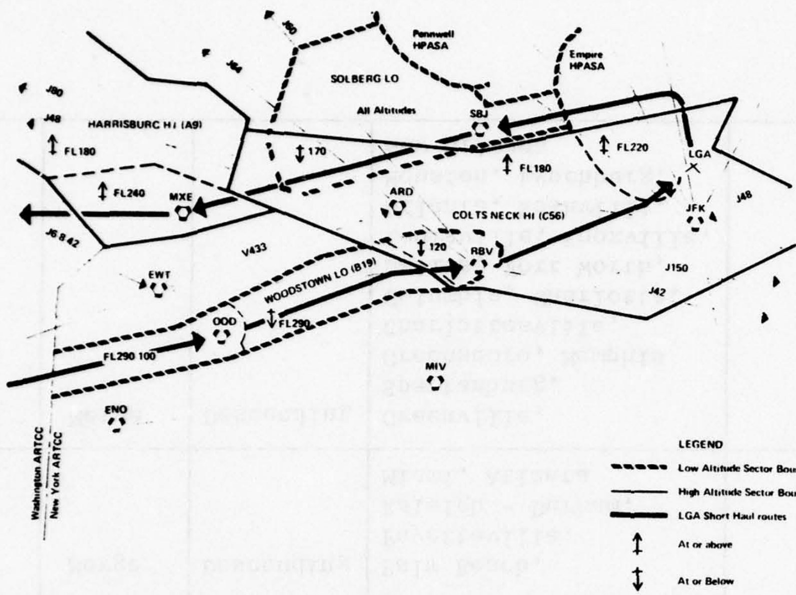


FIGURE 6-6
SECTORIZATION ALONG THE SHORT HAUL ROUTES TO/FROM LaGUARDIA

turbojets along this route were cleared to any altitude at or below FL290, control responsibility would be retained within this sector. Similarly, the Swan Point departure sector in the Washington ARTCC would also be unaffected.

6.4 Consideration of Alternative Solutions

We believe that the New York ARTCC would not impose cruise altitude restrictions procedurally, if they could solve the problems identified in some other, less restrictive way. The following discusses an automated approach to their solution, based on the proceding problem analysis. As the observations upon which that analysis was made are limited, and because the authors have not had an opportunity to discuss with the region and center personnel the results of their findings in detail, this discussion should be regarded as somewhat speculative.

6.4.1 Coordinating Clearances Involving Crossing Conflicts

If the "Solberg to Bel Air" short-haul turbojets were permitted to operate between FL200 and FL260, then during 40 minutes or more of each hour, such flights would encounter no additional traffic conflicts, based on the preceding analysis. However, during the 20 minutes or less of each hour when one or more JFK departures are cleared out J64 or J80, a cruise altitude could be assigned to the short-haul which is higher than the current restriction, but less than and separated from the lowest predicted crossing altitude for the JFK departures. The NAS computer could be programmed to make such a computation for each short-haul departure on request by the Solberg sector controller.

Since under the current sectorization scheme, the higher altitudes are not within the Solberg sector, the computed altitude would have to be approved by the affected high altitude sector controller, (Colts Neck) before it could be assigned to the flight.

If the potential problem of adding an excessive number of handles to the Colts Neck sector is ignored for the moment, it would appear that this controller is in an excellent position to quickly approve (or disapprove) assignment of a computed cruise altitude in his sector. Figure 6-6 shows the fixes and flows the Colts Neck controller actually sees on his Plan View Display (PVD). Specifically, he can see the New York area departures climbing out on their respective routes inbound to his sector, and he can also see the Solberg departures climbing out of LaGuardia, either to the low or high altitude structure. Given the current situation as shown on the PVD, plus the appropriate clearance planning

("strip") data on the Solberg departures, as well as on his other traffic, he should be able to quickly decide whether or not to accept the computed altitude, accept another altitude of his choice, or to deny entry into the high altitude structure. This could be communicated to the Solberg sector via a quick action computer entry. The Solberg controller could then issue the coordinated altitude assignment to the short-haul departure during climbout.

Since the flying distance from JFK to the J64 and J80 intersections with MXE056° radial is about the same as that from LGA, EWR, and the other airports producing short-haul departures, any potential crossing conflicts for one of these short-haul departures will depart JFK about the same time as the short-haul flight departs its airport. Thus, the actual departure times should be obtainable on all potential J64 and J80 conflicts with the short-haul departures before the conflict computation needs to be made. Given that the altitudes being achieved that day by these departures at the intersections of interest are known, a conflict-free cruise altitude for the short-haul departures should be computable, after departure, but before the short-haul reaches Solberg.

The conflict-free cruise altitude could then be automatically displayed at both the Solberg and Colts Neck sector for controller review and approval. Since the flight time for turbojets departing LGA and JFK range between 12 and 16 minutes, sufficient lead time should be available for the computation, display, and coordination process to be completed.

6.4.2 Coordinating Clearances Involving Merging Traffic

If the "Solberg to Bel Air" and/or the "Swan Point to Robbinsville" short-haul turbojets were permitted to operate between FL200 and FL260, instead of FL160/170, then the merges with other high traffic also destined for New York or Washington airports may occur earlier and have a longer common path. For example, if a descent-gradient of between 300 feet and 450 feet per nmi. is assumed between FL260 and altitude 100, then the merges would occur about 20 to 30 miles upstream. In particular:

1. Merging J48 Arrivals with Solberg Short-Hauls to DCA/BAL

   If the J48 arrivals remain at FL220 at the J48 intersection with the MXE056° radial, then in-trail separation would have to be assured upon reaching this intersection, rather than waiting until after the turn to Modena. However, FL220 at this distance from Washington represents a premature descent

for the arrivals from New England. The observed FL220 is probably due to another, but uninvestigated, altitude restriction farther upstream. If this is another fuel problem which can also be solved, then the merge point might well again shift "downstream." In any case, the merge would occur at higher altitudes and would involve descending, perhaps en route metered, aircraft.

2. <u>Merging J150 Arrivals with Swan Point Short-Hauls to LGA</u>

If the J150 arrivals remain at FL250 crossing the center boundary northbound, then in-trail separation would have to be assured by the Washington ARTCC, and prior to handoff to the Woodstown sector. However, the FL250 boundary crossing restriction represents a somewhat premature descent for these arrivals. If this somewhat premature descent could also be eliminated, then the merge point would again shift downstream and would be well within the Woodstown sector. In any case, the merge would occur at higher altitudes and would involve descending, perhaps en route metered, aircraft.

3. <u>J6-8-42 Arrivals with Swan Point Short-Hauls to LGA</u>

If premature descents were avoided for both streams of traffic, then both streams would be descending out of the high altitude structure in the vicinity of New Castle and Woodstown, respectively. The merge could still take place as before, but would involve aircraft transitioning in altitude, rather than aircraft already level at altitude 100.

Based on the above, it appears that additional investigation of the problems of planning and executing clearances to insure safe merges between aircraft during en route descent is required.

Also, since the common route may be longer, it would appear that greater care would be needed to assure that the faster aircraft are sequenced first, or slowed down, to avoid overtakes. However, these problems are an integral part of the en route metering problem discussed in Chapter 1. The solution should be inherent in the design of those en route metering algorithms and control procedures.

With regard to sector design, it would probably be necessary to re-align sector boundaries to insure that the aircraft are under the control of one sector during the time when the merge is taking place. How this might be done was not addressed.

6.4.3 Reducing the Operational Constraints Imposed by Limited Sector Control Capacities

Even if the problems of coordinating conflict-free clearances can be solved, the question of how many aircraft a radar controller, such as at the Colts Neck High sector, can handle remains. If it should turn out that it is the overhead problem of "N handles", and not the traffic control problem of "N^2 conflicts", that inhibits ATC from accommodating the short-hauls at the higher altitudes, then resectorization to again balance controller workloads should be addressed.

APPENDIX A

DESCRIPTION AND APPLICATION OF TWO COMPUTER MODELS USED

A.1 Landing Delay Model for En Route Metering

The curves plotted in Figures 3-2 and 2-3 were derived from a digital computer model developed by Ann Hunt of Metrek. The model computes the landing delays needed to properly sequence and space arrivals to a single runway of specified capacity. The model is written in the compiler language of IBM's General Purpose Simulation System (GPSS) and was run with input parameters representing the present Denver profile descent geometry to runway 26L.

The input parameters to the model include the average rate of randomized arrivals to the airport each hour, the percentage of arrivals via each feeder fix, the delivery accuracy of the en route metering process at the feeder fix, and the minimum permissible landing interval at the runway threshold. Planned sequencing and spacing (the initial scheduling of landing times) is done using a first-come-first-served landing sequence.

Arrivals are randomly generated to meet the specified hourly demand rate and are sequentially scheduled to the runway relative to the specified minimum permissible landing interval (which corresponds to the runway capacity, or maximum safe throughput desired). Subtracting the flying time to the runway for each arrival gives the desired feeder fix crossing time. The actual feeder fix crossing time is computed as the desired value plus an en route metering error which is normally distributed with a mean of zero and a standard deviation of 1 minute.

The total delay for each arrival is the sum of that imposed at the feeder fix (actual crossing time minus the undelayed time), that imposed to insure safe spacings in-trail along each route (computed from statistical flying time deviations from feeder fix to runway), and that imposed at each merge point, to the runway. The expected delay is the average for all arrivals during the hour.

Successive runs were made at increasing demand levels for each specified minimum permissible landing interval (corresponding to 35 or fewer landings per hour). Since the arrival demand rate was not varied over the hour, the effects of demand peaking are not included.

A.2 Runway Capacity Estimation Model

For the purposes of the analysis of Section 3.5, the analytical model for computing runway capacities described in Reference 3-11 was used. A brief description follows.

The analytic model exists as a digital computer program and was designed "for use in the study of the impact of separation standard changes." Given some 18 different input parameters (some multi-valued), it can compute the:

1. Error-free inter-arrival time over the runway threshold.

2. Average inter-arrival time over the threshold given the prescribed error distribution parameters.

3. Maximum safe capacity of the runway which results.

4. Maximum safe capacity of the runway, given both arrivals and departures for a 50-50 mix (perfect inter-leaving).

Of the input parameters, 11 parameters specify the important approach path dimensions, estimation error values, and procedural rules. Another five parameters specify the aircraft class mix and the other performance characteristics (speed profiles) of each class. The remaining two parameters specify the separation standards to be applied between each possible aircraft class pair for both arrivals and departures.

A limitation important to the interpretation of the results of this study is that a simple two-valued velocity profile is assumed for each aircraft type. Any aircraft of a given type is assumed to cross the ATC gate location at a constant initial speed, and then to decelerate instantaneously to its final approach speed at a second specified location between the gate and the runway threshold. As a consequence, the deceleration profiles of reduced flap and delayed-flap approach procedures can only be approximated.

APPENDIX B

AN AIRCRAFT FUEL CONSUMPTION MODEL

The time taken, the distance required, and the fuel consumed by an aircraft in climbing at a true airspeed of v from an altitude h_1 to h_2 can be derived from the basic equations of motion, as illustrated in **Figure** B-1. The algebriac sum of the forces acting longitudinally (thrust, drag, and the longitudinal component of its weight) on an aircraft of mass W/g produces a longitudinal acceleration of dv/dt yields:

$$T-D-W \sin \gamma = \frac{W}{g}\frac{dv}{dt} = \frac{W}{g} \cdot \frac{dv}{dh} \cdot \frac{dh}{dt} \qquad \text{(B-1)}$$

And from Figure A-1:

$$\text{Rate of Climb, } R/C = \frac{dh}{dt} = v \sin \gamma \qquad \text{(B-2)}$$

From equations B-1 and B-2:

$$R/C = \frac{\left(\frac{T-D}{W}\right) v}{\left(1 + \frac{v}{g} \frac{dv}{dh}\right)} \qquad \text{(B-3)}$$

The acceleration factor $\frac{v}{g}\frac{dv}{dh}$ can be found from Figure B-2. The drag-to-weight ratio (D/W) is approximately equal to the inverse of the lift-to-drag ratio since the climb gradient γ is typically a very small angle. From Reference B-1, a typical lift-to-drag (L/D) ratio for a turbojet transport like the B727 is 17.

To obtain the relationship between the thrust (T) required and the fuel consumed to achieve it, three JT8D-7 Pratt and Whitney engines were assumed, thus making the model representative of some B727 aircraft. The Thrust (T) versus specific fuel consumption (SFC) relationships for these engines were obtained from Reference B-2, for engine performance at sea level, 5,000 feet, and 10,000 feet. Thrust and specific fuel consumption at intermediate altitudes were obtained by interpolation.

Using the rate of climb from equation B-3, the time, distance and fuel consumption were obtained by integrating flight motion over the desired altitude as follows.

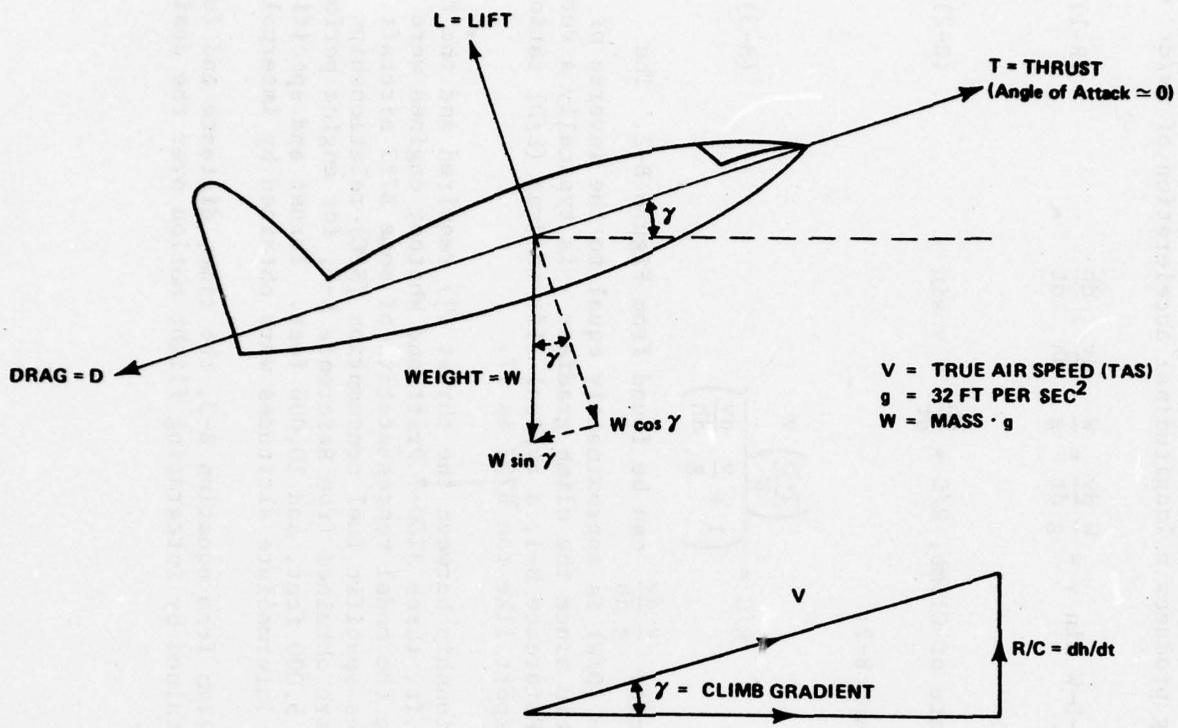


FIGURE B-1
FORCES ACTING ON A CLIMBING AIRCRAFT

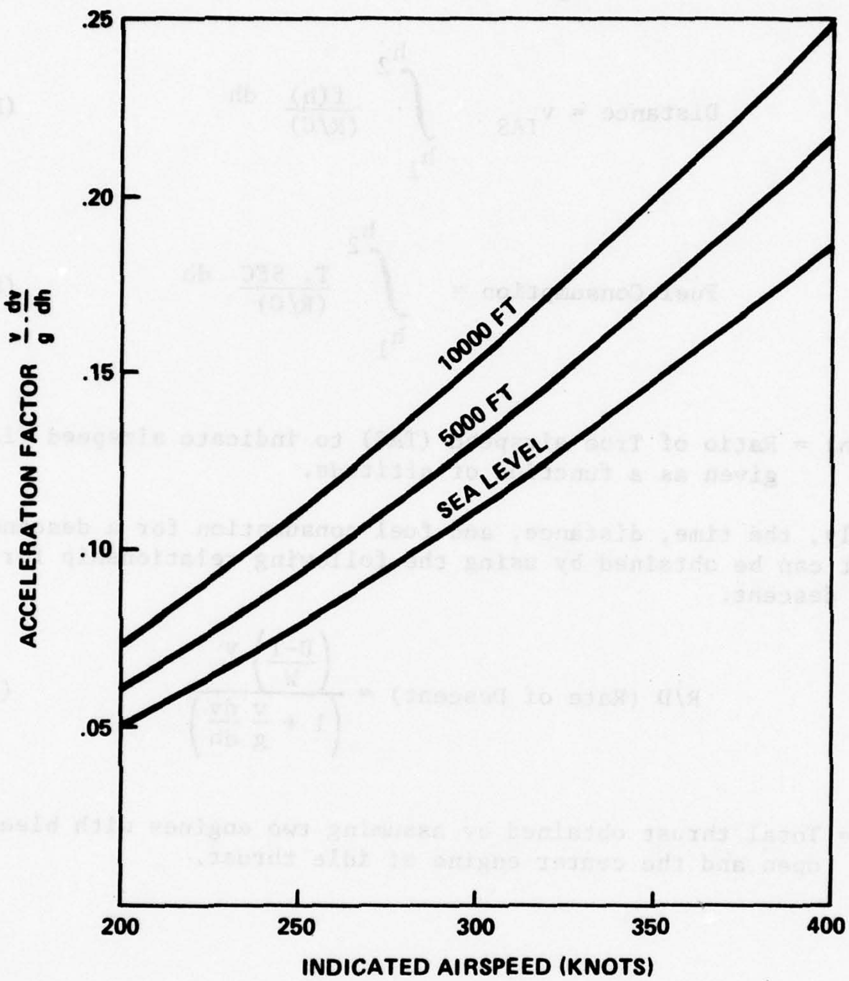


FIGURE B-2
ACCELERATION CORRECTION FACTOR FOR A CLIMBING OR DESCENDING FLIGHT

$$\text{Time} = \int_{h_1}^{h_2} \frac{1}{(R/C)}\, dh \qquad \text{(B-5)}$$

$$\text{Distance} = v_{IAS} \int_{h_1}^{h_2} \frac{f(h)}{(R/C)}\, dh \qquad \text{(B-6)}$$

$$\text{Fuel Consumption} = \int_{h_1}^{h_2} \frac{T.\ SFC}{(R/C)}\, dh \qquad \text{(B-7)}$$

Where

$f(h)$ = Ratio of True airspeed (TAS) to indicate airspeed (IAS) given as a function of altitude.

Similarly, the time, distance, and fuel consumption for a descending aircraft can be obtained by using the following relationship for the rate of descent.

$$\text{R/D (Rate of Descent)} = \frac{\left(\frac{D-T}{W}\right) v}{\left(1 + \frac{v}{g}\frac{dv}{dh}\right)} \qquad \text{(B-8)}$$

Where

T = Total thrust obtained by assuming two engines with bleeds open and the center engine at idle thrust.

APPENDIX C

ESTIMATION OF THE NUMBER OF CIVIL TURBOJET FLIGHTS WHICH MIGHT BENEFIT ANNUALLY

According to Reference 1-3, there were more than 4.5 million Certificated Route Air Carrier departures during CY 1975, of which about 2.4 million departed Large Hubs (TCA locations) and about 0.9 million departed Medium Hubs (TRSA locations). All but about 6% of these departures can be assumed to have been turbojet (including turbofan) aircraft, given that only about 6% of the air carrier fleet is piston or turboprop and assuming an equivalent utilization rate for all air carrier aircraft. Supplemental, Foreign Flag, and Intra-State air carriers accounted for an additional 7% of the departures in public air transportation in CY 1974 (Reference C-1).

To form an estimate of the maximum number of turbojet operators which might benefit annually from the per-flight savings in this report, the assumption is made that the number of turbojet departures by civil operators other than Certificated Route Air Carriers is just equal to the number of non-turbojet departures included in the Certificated Route Air Carrier data. Consequently, the maximum number of civil turbojet departures (or arrivals) which might benefit annually is:

Civil Turbojets	Annual Operations
To/from TCAs	2.4M (assume 1.5M suffer landing delays)
To/from TRSAs	0.9M
Annual Total	4.5M

Of the total, analysis of Reference 1-3 reveals the following distribution across aircraft types:

2 engine, regular-body (DC9, B737)	34.0%
3 engine, regular-body (B727)	34.5%
4 engine, regular-body (B707, DC8)	8.5%
4 engine, wide-body (DC10, L1011)	5.0%
	82.0%

On this basis, it assumed that the B727 is fairly representative of the average civil turbojet transport in terms of fuel burn in those analyses where all turbojets potentially stand to benefit (Chapters 2, 3, 4).

APPENDIX D

ESTIMATION OF THE FUEL SAVINGS OF INCREASING THE NUMBER OF FLIGHT LEVELS ABOVE FL290

D.1 Estimation of the Fuel Savings to the Average Medium or Long-Haul Flight

The expected (average) fuel penalty paid by the average medium/long-haul flight operating fuel-conservatively in either the current 3-level flight level structure or one of the alternative 4-level structures discussed in Chapter 5 can be expressed as:

$$\text{Expected Fuel Penalty} = \int_{o}^{z_m} f(z) \cdot p(z) \cdot dz$$

where: z = the difference between the lower usable right-way flight level, or the upper usable right-way flight level, and the fuel optimum cruise altitude, whichever is closer.

z_m = the maximum of value of z and is equal to the vertical separation standard, since the worst case occurs when the optimal altitude lies mid-way between the upper and lower right-way flight levels.

$f(z)$ = excess fuel-burn as a function of z, expressed as a percentage of the total cruise burn.

$p(z)$ = the probability density function of z for all medium and long-haul flights.

The deviation of the above functions and their evaluation follows.

First, the Boeing data given in Chapter 5 is transformed into $f(z)$ by the following argument. The excess mileage fuel penalty given by Boeing, and here called $x(z)$, can be approximated as a linear function of z for turbojet aircraft flown at constant mach:

$z(10^3$ feet)	x = Percent Fuel Mileage Penalty
+2	2%
0	0
-2	2
-4	4

Or, for this range of z, in 1000's of feet:

$$x = |z| \, ^{o}/o$$

For the purpose of this study, f(z) for the average cruise length is desired, instead. Since the mileage achievable from a given amount of fuel is reduced to (1 - x) per mile if a non-optimum altitude is flown, the total fuel burned for the average cruise length (L) is found by:

$$F_o = k \cdot L(1 - x)$$

$$dF = k \cdot Lx$$

$F_o + dF$ = total fuel burned in L miles at the non-optimal altitude

where: F_o = the fuel burned at the optimal altitude

dF = the excess fuel burned at the non-optimal altitude

k = rate at which fuel is burned per mile at the non-optimal altitude.

The percent of excess fuel burn, f(z), is then:

$$f = \frac{dF}{F_o} = \left(\frac{x}{1 - x}\right) 100 \, ^{o}/o$$

For values of x less than 7%, (1 - x) is approximately one, and

$$f(z) = x(z).$$

To find the probability density function, p(z), for the optimal cruise altitude is z feet away from the nearest right-way flight level, it is noted that for a given flight, the optimal cruise altitude is a function of the rate at which fuel weight burns off, increasing as the aircraft becomes lighter. Averaged across all aircraft types, payload weights, outside air temperatures, and cruise lengths, the value of optimal cruise altitude can be considered uniformly distributed between two adjacent right-way flight levels. That is,

$$p(z) = \text{constant} = \frac{1}{z_m}$$

Since,

$$\int_o^{z_m} p(z) \, dz = 1.$$

The average value of the percent excess fuel burn is then:

$$f = \int_0^{z_m} f(z) \cdot p(z)dz = \frac{1}{z_m} \int_0^{z_m} |z|\, dz = \frac{z_m}{2}\ \%$$

For the alternatives considered:

Flight Levels Each Way	Vertical Separation Standard		Average Excess Fuel ($\bar{f}$)	
3	2000' (FL290-390)	0.25%	1.0%	
4	1500' (FL290-390)	Saving	0.75%	0.5%
4	1000' (FL290-330)		0.5%	Saving

That is, the potential fuel benefit of going to the 1,500 foot standard averages 0.25% of the total cruise burn for any medium or long-haul flight operating fuel-conservatively between FL290 and FL390. Similarily, the potential benefit of going to the 1,000 foot standard up to FL330 averages 0.5% of the total cruise burn for those medium or long-haul flights operating fuel conservatively between FL290 and FL330.

D.2 Estimation of the Average Annual Fuel Consumption During Medium and Long-Haul Flights Over Optimum Altitudes

Depending upon its weight, a specific type of aircraft will have minimum fuel requirements when it cruises at Long-Range Cruise (LRC) speed at a certain altitude defined as the best (optimum) cruise altitude. During cruise the weight of the aircraft gradually decreases with the consumption of fuel, thereby changing both the LRC speed and the optimal altitude. Assume that all flights can operate unconstrained at their optimal altitudes and speeds. If the annual cruise fuel burn for all such flights can be estimated, then the percent fuel savings computed in D.1 can be applied, and an estimate of the potential annual savings of jet fuel in gallons can be obtained.

At any altitude, the average fuel consumption (representing an average of the minimum fuel requirements for all flights operating at that altitude) can be obtained by computing the average fuel consumption per nmi and then multiplying by an average length of medium and long-haul cruise flight paths. The minimum fuel consumption per nmi at a certain altitude has been computed by considering the optimum weight at the chosen altitude and a constant Cruise Mach (CM) speed for that weight and altitude. The average fuel consumption per nmi is then obtained from the following equation.

$$\text{Average Fuel Consumption/nmi} = \frac{1}{n} \sum_{A=1}^{n} FF_A(\text{Wopt.},CM)$$

Where: $FF_A(\text{Wopt.},CM)$ = Fuel flow lbs/nmi for an aircraft of weight Wopt. cruising at mach CM at flight level A

Wopt. = Weight of aircraft that would require minimum fuel at flight level A

A = Flight level between 290 and 390 or 330 with n available intermediate levels

CM = Constant Cruise Mach speed nearest to LRC for Wopt. and flight level A

The average fuel consumptions/nmi over flight levels 290 to 330 and over flight levels 290 to 390 for B-727-200 and L-1011 have been compiled and shown respectively in Tables D-1 and D-2.

In this analysis, fuel consumption for a B-727-200 aircraft is assumed to represent the fuel consumption for an average conventional aircraft. Since the average fuel consumption of a regular-bodied four engine turbofan aircraft is higher than that of a B-727-200, an average stage length (Reference D3) for regular-bodied four engine turbofan aircraft is assumed to represent an average length of medium and long-haul conventional flights. It is assumed that the extra flight length (difference between average stage lengths of four engine turbofan and three engine turbofan aircraft) for all three engine aircraft flights would compensate for the extra fuel required for the four engine aircraft and also compensate for the reduction in average stage length due to the fact that the short-haul flights are also included in computing the overall average stage length. Similarly, the fuel consumption for an average heavy aircraft and the average stage length of wide-bodied four engine turbofan aircraft is assumed to represent an average length of all heavy aircraft over medium and long-haul flights.

Hence,

Average stage length of conventional aircraft = 906 nmi

Average stage length of heavy aircraft = 1776 nmi

As indicated in Section D.1, two cases of reduced vertical separation have been considered in this report; i.e., (1) reduction of vertical separation from 2,000 feet to 1,500 feet between flight levels 290 to 390, and (2) reduction of vertical separation from 2,000 feet to 1,000 feet between flight levels 290 to 330 plus maintaining present 2,000 foot separation above flight level 330.

TABLE D-1

FUEL CONSUMPTION AT OPTIMUM ALTITUDES FOR B-727-200 [D1]

OPTIMUM FL. LEVEL	OPTIMUM WEIGHT (1000 LBS.)	FUEL CONSUMPTION AT 0.80* MACH (LBS/NMI)	CLIMB DISTANCE TO OPTIMUM ALTITUDE (NMI)	DESCENT DISTANCE FROM OPTIMUM ALTITUDE (NMI)
290	195	23.31	140	81
300	190	22.69	140	83
310	180	21.54	133	85
320	170	21.01	128	87
330	165	19.85	128	89
340	160	19.31	128	91
350	150	18.13	121	93
360	140	17.04	114	95
370	135	16.48	114	97
380	130	15.93	114	99
390	120	14.09	108	101
	AVERAGE OVER FL. LEVELS 290 TO 330	21.68	133	85
	AVERAGE OVER FL. LEVELS 290 to 390	19.1	124	91

* CONSTANT CRUISE MACH NEAREST TO LRC

TABLE D-2

FUEL CONSUMPTION AT OPTIMUM ALTITUDES FOR L-1011[D2]

OPTIMUM FL. LEVEL	OPTIMUM WEIGHT (1000 LBS.)	FUEL CONSUMPTION AT 0.82* MACH (LBS./NMI)	CLIMB DISTANCE TO OPTIMUM ALTITUDE (NMI)	DESCENT DISTANCE FROM OPTIMUM ALTITUDE (NMI)
290	430	39.3	198	100
310	390	35.8	175	107
330	350	32.4	155	115
350	320	29.7	145	123
370	290	27.0	136	131
390	260	24.5	127	139
	AVERAGE OVER FL. LEVELS 290 TO 330	35.8	176	107
	AVERAGE OVER FL. LEVELS 290 TO 390	29.8	156	123

* CONSTANT CRUISE MACH NEAREST TO LRC

Average cruise length* for conventional aircraft between fl. levels 290 to 390 = 691 nmi

Average cruise length for conventional aircraft between fl. levels 290 to 330 = 688 nmi

Average cruise length for heavy aircraft between fl. levels 290 to 390 = 1497 nmi

Average cruise length for heavy aircraft between fl. levels 290 to 330 = 1493 nmi

Using the average fuel consumptions/nmi from Tables D-1 and D-2

Average fuel consumption/flight between fl. levels 290 to 390 for conventional aircraft = 13198 lbs (1941 gals.)

Average fuel consumption/flight between fl. levels 290 to 330 for conventional aircraft = 14916 lbs. (2194 gals.)

Average fuel consumption/flight between fl. levels 290 to 390 for heavy aircraft = 44611 lbs. (6560 gals.)

Average fuel consumption/flight between fl. levels 290 to 330 for heavy aircraft = 53449 lbs. (7860 gals.)

Table D-3 determines an average ratio of conventional to heavy aircraft based on the data from airlines that are expected to operate medium and long-haul flights. Since the statistics on the number of operations also include short hauls, some of the other airlines, that may be flying medium hauls as well, have been excluded from Table D-3. Since the number of cargo operations are small, they have also not been considered in Table D-3.

Reference D5 indicates that on a specific day (August 6 1976) there were 5031 scheduled flights over 400 miles.** Assuming this also as the daily average of the number of flights over 400 miles, and taking the average ratio of conventional to heavy aircraft from Table D-3,

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* Average cruise length is obtained by subtracting average climb plus descent distances to the optimum altitudes for average stage length.

** This source includes all scheduled flights listed in the Official Airline Guide including domestic trunk, local service, international, air commuter and intrastate passenger, and all-cargo operations.

TABLE D-3

AIRLINES'* DOMESTIC OPERATIONS** DURING 1975 AT MAJOR AIRPORTS (C4)

AIRPORT	AIRLINE	CONVENTIONAL AIRCRAFT OPERATIONS	HEAVY AIRCRAFT OPERATIONS	% HEAVY AIRCRAFT OPERATIONS
	DELTA	71372	11125	
	EASTERN	71138	2813	
ATLANTA	NORTHWEST	2208	1379	
(HARTSFIELD)	UNITED	10829	681	
	TOTAL	155547	15998	9.33
	AMERICAN	10417	825	
	DELTA	17950	506	
BOSTON	EASTERN	19284	309	
(LOGAN)	TWA	5723	1126	
	UNITED	3598	846	
	TOTAL	56972	3612	5.96
	AMERICAN	35625	5185	
	DELTA	25078	2086	
CHICAGO	EASTERN	10423	377	
(O'HARE)	NORTHWEST	10845	8986	
	TWA	32614	2987	
	UNITED	56852	9993	
	TOTAL	171437	29614	14.73

* AIRLINES OPERATING MEDIUM AND LONG-HAUL FLIGHTS

** DOES NOT INCLUDE CARGO

TABLE D-3

AIRLINES' DOMESTIC OPERATIONS DURING 1975 AT MAJOR AIRPORTS (C4)

(CONTINUED)

AIRPORT	AIRLINE	CONVENTIONAL AIRCRAFT OPERATIONS	HEAVY AIRCRAFT OPERATIONS	% HEAVY AIRCRAFT OPERATIONS
	AMERICAN	37548	1969	
DALLAS/FT. WORTH	BRANIFF	48179	343	
	DELTA	14009	3109	
	TOTAL	99736	5421	5.16
	CONTINENTAL	13513	4349	
DENVER	TWA	6090	184	
(STAPLETON)	UNITED	21431	3820	
	WESTERN	9229	202	
	TOTAL	50263	8555	14.54
	AMERICAN	11548	1659	
DETROIT	DELTA	9488	3451	
(METROPOLITAN)	EASTERN	3822	145	
	NORTHWEST	8920	2993	
	UNITED	4920	1687	
	TOTAL	38698	9935	20.43
	AMERICAN	13247	4919	
	CONTINENTAL	6367	5792	
LOS ANGELES	DELTA	3042	2744	
(INTERNATIONAL)	EASTERN	843	247	
	NORTHWEST	156	1582	
	TWA	12098	4236	
	UNITED	23474	6061	
	WESTERN	22076	1335	
	TOTAL	81303	26916	24.87

TABLE D-3

AIRLINES' DOMESTIC OPERATIONS DURING 1975 AT MAJOR AIRPORTS (C4)

(CONTINUED)

AIRPORT	AIRLINE	CONVENTIONAL AIRCRAFT OPERATIONS	HEAVY AIRCRAFT OPERATIONS	% HEAVY AIRCRAFT OPERATIONS
	CONTINENTAL	1210	236	
MIAMI	DELTA	13492	1448	
(INTERNATIONAL)	EASTERN	25242	2514	
	NATIONAL	7207	3292	
	NORTHWEST	1344	1087	
	UNITED	2326	248	
	TOTAL	50821	8825	14.80
	AMERICAN	6951	2302	
NEW YORK	DELTA	6391	900	
(JFK)	EASTERN	11210	4170	
	NATIONAL	5446	699	
	NORTHWEST	400	1441	
	TWA	5577	1989	
	UNITED	3838	1979	
	TOTAL	39813	13480	25.29
	AMERICAN	29745	1137	
NEW YORK	EASTERN	29912	1693	
(LGA)	NATIONAL	1682	332	
	TWA	14230	-	
	UNITED	7007	6	
	TOTAL	82576	3168	3.69

TABLE D-3

AIRLINES' DOMESTIC OPERATIONS DURING 1975 AT MAJOR AIRPORTS (C4)

(CONCLUDED)

AIRPORT	AIRLINE	CONVENTIONAL AIRCRAFT OPERATIONS	HEAVY AIRCRAFT OPERATIONS	% HEAVY AIRCRAFT OPERATIONS
	DELTA	8672	356	
PHILADELPHIA	EASTERN	11046	1085	
(INTERNATIONAL)	NORTHWEST	2209	1317	
	TWA	7796	798	
	UNITED	6424	801	
	TOTAL	36147	4357	10.76
	AMERICAN	6879	2124	
SAN FRANCISCO	DELTA	1611	1251	
(INTERNATIONAL)	NATIONAL	758	718	
	NORTHWEST	497	987	
	TWA	9972	2275	
	UNITED	31697	3513	
	WESTERN	14267	360	
	TOTAL	65681	11228	14.60
	AMERICAN	4359	579	
WASHINGTON D.C.	NORTHWEST	563	296	
(DULLES)	TWA	2676	210	
	UNITED	3994	336	
	TOTAL	11592	1421	10.92
			NATIONAL AVERAGE OF HEAVY AIRCRAFT OPERATIONS	13.5%

the number of conventional and heavy aircraft flying over 400 nmi per day can be computed as 4352 (87%) and 679 (13%) respectively.

Reference D6 shows that on a peak IFR day 37% of all the turbojet operations above fl. level 290 remained between fl. levels 290 and 330. Based on the above mentioned flights over 400 nmi, the number of conventional and heavy aircraft between fl. levels 290 and 330 can be estimated as 1610 and 251 respectively.

Hence,

Between fl. levels 290 and 390

Average fuel consumption/day by conventional aircraft = 57.44 million lbs.

Average fuel consumption/day by heavy aircraft = 30.29 million lbs.

Total average fuel consumption/day of all medium and long-haul flights = 87.73 million lbs.

Annual average fuel consumption of all medium and long-haul flights = 32021.45 million lbs. or 4709.04 million gallons at 6.8 lbs. per gallon

Estimated savings by reducing vertical separation from 2000 feet to 1500 feet (at 0.25%) = 11.77 million gallons

Between fl. levels 290 and 330

Average fuel consumption/day by conventional aircraft = 24.01 million lbs.

Average fuel consumption/day by heavy aircraft = 13.42 million lbs.

Total average fuel consumption/day of all medium and long-haul flights = 37.43 million lbs.

Annual average fuel consumption of all medium and long haul flights = 13661.95 million lbs. or 2009.11 million gallons at 6.8 lbs. per gallon

Estimated savings by reducing vertical separation from 2000 feet to 1000 feet (at 0.5%) = 10.05 million gallons

APPENDIX E

ANALYSIS OF DATA COLLECTED AT THE NEW YORK ARTCC

Two of the authors spent two days at the New York center in July 1976, in order to better understand the problems ATC has in accepting short-haul turbojets into the high altitude structure between Washington, D.C. and New York. In particular, data was to be collected on the frequency and type of potential conflicts that might occur if the short-haul turbojets were allowed to cruise as high as FL260 or 270.

The potential conflicts data was collected by the authors at a spare sector position which was equipped with a "see-all" plan view display, flight strip printer, and a computer entry device. Every tracked aircraft which appeared as in-bound on one of the routes of interest was recorded as follows:

1. An automatically-printed flight strip was requested based on the aircraft's flight of computer identification. This provided the data on aircraft type, flight plan and assigned altitude.

2. The clock time and reported altitude at entry into the sector and/or at the point of potential conflict was recorded on the strip. Other explanatory notes were recorded, based primarily on information that could be obtained by relating these tracks and the data in their full data blocks, to the procedures and maps provided by Reference 6.5.

There was no opportunity to monitor the controller's voice channel, so no data was collected directly on the clearances issued or when they were issued. What the data permits is an analysis of what the aircraft observed actually did as a result of these unrecorded clearances.

Table E-1 summarizes the short-haul turbojet operations observed on the "Solberg to Bel Air" route from LGA/EWR to DCA. Table E-5 summarizes the short-haul turbojets observed on the "Swan Point to Robbinsville" route from DCA/IAD/BAL to LGA. Eastern Electras, Allegheny Convair 580s, and other turboprop and piston aircraft were ignored, since they would typically not want higher altitudes.

"Potential conflicts" for these short-hauls, should they be cleared for higher altitudes, were assumed to be flights between FL180 and FL290 which are cleared via routes which cross, or merge with, the short-haul routes. Those observed are summarized in Tables E-2, E-3

TABLE E-1

IFR TURBOJETS OBSERVED ON THE "SOLBERG TO BEL AIR" ROUTE (V3..V378)

Friday, 23 July 1976: 1130-1630Z (7:30 am to 12:30 pm EDT)

LGA DEPARTURES FOR DCA/BAL

Typical route clearances = LGA.RNGO8.SBJ.V3.MXE.V378.BAL..DCA
RNGO8 = Ringoes 8 SID = Vectors to SBJ.

Observed	Flights	Assigned/Reported Altitude Crossing Solberg	Number Over Solberg Each Hour, 1130 to 1630Z
1	LR24	160C	2, 1, 2, 0, 3
6	DC9 or B727	160C	
1	DC9	140C	
8			

EWR DEPARTURES FOR DCA/BAL

Typical route clearance = EWR.SMST5.SBJ.V3.MXE.V378.BAL..DCA
SMST5 = Somerset 5 SID = Vectors to SBJ.

Observed	Flights	Assigned/Reported Altitude Crossing Solberg	Number Over Solberg Each Hour
4	DC9 or B727	160/90 to 110	0, 3, 0, 1, 0

HPN (White Plains) and MMU (Morristown Mun.) DEPARTURES FOR DCA/BAL

Typical route clearance = HPN/MMU...V3.MXE.V378.BAL..DCA

Observed	Flights	Assigned/Reported Altitude Crossing Solberg	Number Over Solberg Each Hour
2	DC9 or BA11	160C	1, 2, 1, 0, 0
1	FFJ	140/90	
1	FFJ	120C	
4			

TOTALS

Turbojets, SBJ...BAL/DCA = 16 in five hours (3 per hour, average)
Maximum cruise altitude for all flights observed = 160

TABLE E-2

OBSERVED IFR TRAFFIC ON J64 OVERFLYING V3

Friday, 23 July 1976: 1130-1630Z (7:30 am to 12:30 pm)

JFK DEPARTURES FOR POINTS WEST:

Typical route clearances = JFK.FREH7.RBV.J64...
FREH7 = Freehold 7 = Vectors to RBV

Observed Flights		Destination	Assigned/Reported Altitude Crossing V3	Number Over V3 Each Hour
1	B747	ORD	390/250	0, 1, 1, 1, 1
1	B707	DEN	350/290	
1	L1011	SFO	350/200	
1	B707	SFO	390/230	
4				

TABLE E-3

OBSERVED IFR TRAFFIC ON J80 OVERFLYING V3

Friday, 23 July 1976: 1130-1630Z (7:30 am to 12:30 pm EDT)

JFK AND LGA DEPARTURES FOR POINTS WEST

Typical JFK route clearance = JFK.FREH7.RBV.J80...
FREH7 = Freehold 7 SID = Vectors to RBV

or

Typical LGA route clearance = LGA.HOLM7.RBV.J80...
HOLM7 = Homdel 7 SID = Vectors to RBV

Observed	Flights	Destination	Posted/Reported Altitude Crossing V3	Number Over V3 Each Hour
1	B747	LAX	P350/220	4, 3, 4, 4, 2
4	L1011	LAS, LAX, SFO	P350/220 to 240	
6	B727 or DC9	CMH, STL, BNA, DFW	P310, 350/240 to 300	
6	B707 or DC8	DEN, SEA, SFO PNX, LAS, LAX	P310,350/240 to 300	
17				

TABLE E-4

OBSERVED IFR TRAFFIC ON J48 BELOW FL290
MERGING ONTO V3

Friday, 23 July 1976: 1130-1630Z (7:30 am to 12:30 pm)

BAL/DCA ARRIVALS FROM NEW ENGLAND:

Typical route clearance = ...JFK263(J48)..MXE056(V3).MXE.V378.9EX..DCA

or ...V378.V93.7JA..BAL

Observed	Flights	Origin	Assigned/Reported Altitude Turning onto MXE056	Number Merging onto V3 Each Hour
8	B727 or DC9	YUL, BOS, BDL	220C, typical*	2, 2, 2, 2, 2
2	BA11	BDS	220C	
10				

* But descent to lower assigned altitudes is begun shortly after turn.

TABLE E-5

IFR TURBOJETS OBSERVED ON THE
"SWAN POINT TO ROBBINSVILLE" ROUTE (V123)

Thursday, 23 July 1976: 2100-2400Z (5:00 pm to 8:00 pm EDT)

DCA/IAD DEPARTURES FOR LGA:

Typical route clearance = ...7NP.V123.RBV.PROUD1.LGA
PROUD1 = Proud 1 STAR = RBV054...LGA221.LGA

Observed Flights*		Posted Cruise Altitude	Assigned/Reported Altitude Crossing OOD	Number Over Woodstown Each Hour
1	G2	190	110/160	0, 1, 4
4	B727 or DC9	170	100,110/170 to 150	
5				

* Note that turboprop aircraft are not included, specifically four L188 Electras (Eastern) and one Convair 580 (Allegheny). If these aircraft were included in the hourly counts, the result would be 4, 1, 5.

TABLE E-6

OBSERVED IFR TRAFFIC ON J6-8-42 TO MERGE WITH V123 TRAFFIC

Thursday, 22 July 1976: 2100-2400Z (5:00 pm to 8:00 pm EDT)

LGA ARRIVALS FROM POINTS WEST AND SOUTHWEST:

Typical route clearance = ...J6.CSN.J8 (or J42).EWT.PROUD1.LGA
PROUD1 = Proud 1 STAR = RBV054...LGA221.LGA

Observed Flights		Origin	Assigned/Reported Altitudes: After Center Boundary	Assigned/Reported Altitudes: At Newcastle	Number Over Newcastle Per Hour
1	FFJ	MEM	250/?	100C	
11	B727 or DC9	IAH, DFW, MSY SDF, ATL CLT, GSO CAE, GSP	100/240 120/240	100/240 to 150 120/240	4, 4, 8
3	737	TYS, LYH, CHO	100/240	100/210 to 180	
1	BE90	Hazard, Ky.	100/190	100/100	
16					

TABLE E-7

OBSERVED IFR TRAFFIC DEPARTING WASHINGTON OR ARRIVING NEW YORK VIA J150

Thursday, 22 July 1976: 2100-2400Z (5:00 pm to 8:00 pm EDT)

LGA ARRIVALS FROM POINTS SOUTH:

Typical route clearance = ...J150.OOD.OOD053..RBV249.RBV.PROUD1.LGA
PROUD1 = Proud 1 STAR = RBV054...LGA221.LGA

Observed	Flights	Origin	Assigned/Reported Altitudes At Center Boundary	Number Across Boundary Per Hour
1	B727	ATL	250C	3, 1, 2
4	B727	MIA, PBI, RDU	100/250 to 200	
1	B737	FAY	250C	
6				

DCA/IAD DEPARTURES FOR POINT NORTH:

Typical route clearance = DCA/IAD...7NP.V123.RBV.J150...(Handoff to Colts Neck high in the vicinity of Woodstown)

Observed	Flights	Destination	Assigned/Reported Altitudes At Boundary	At Woodstown	Number Across Boundary Per Hour
1	B707	Gander		330C	1, 3, 4
1	FFJ	BOS		290C	
4	B727 or DC9	BOS	240/220 (1)	290/220 to 250	
1	DC9	PVD	250/210	250C	
1	DC9	BDL	210C	210C	
8					

and E-4 for the "SBJ to 7BH" route and in Tables E-6 and E-7 for the "7PN to RBV" route.

In addition to these "potential conflicts", data was taken on the flights which depart the terminal area initially in-trial with the short-haul departures, but which are bound for higher altitudes. In particular, Washington area departures for points north, but in-trail over Swan Point, are tabulated separately in Table E-7. New York area departures for points west via J60 and LRP077°, but in-trial until reaching Solberg, are not analyzed in detail.* These departures are not considered to be "potential conflicts" since they are initially separated by the TRACON in-trail, and are subsequently separated by lateral route divergence (after SBJ).

E.1 Analysis of the Potential Conflicts with the "Solberg to Bel Air" Short-Hauls

The potential for high altitude conflicts is discussed below on a route-by-route basis. The conflict statistics for those routes which actually provided conflicting traffic are summarized in Table 6-3.

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* For the record, it should be noted that the in-trail departures over Solberg (SBJ) constituted the busiest of all the routes for which data was taken:

LGA/EWR/TEB Departures for J60

Typical route clearance = LGA.RNG08.SBJ.SBJ265..ETX112.ETX.J60..

LGA/EWR/TEB Departures for J75, J80-110, J48

Typical route clearances = LGA.RNG08.SBJ.SBJ259..LRP077.. LRP258..J80...

or

EWR.SMST5.SBJ.SBJ259..LRP077..J75...

During the period 1130-1630Z on Friday, 23 July 1976, the following departure routes over SBJ were observed:

for J60:
26 departures in five hours

for J75, 80-110, J48:
23 departures in five hours

J60: Since the New York area departures for both Washington and points west via J60 and the LRP077° radial are routed out over Solberg in-trail by the New York common IFR Room (NYCIFRR), changing the assigned altitudes (to which the departures bound for Washington are climbing) should add no problem for ATC. Published J60 terminates at Robbinsville, and no flights were observed to use the J60 segment between East Texas (ETX) and Robbinsville (RBV). It would appear that the intersection of J60 with the SBJ..9EX route is usually empty.

J64 and J80: These two routes provide the principal potential for crossing conflicts with southbound short-hauls wanting higher altitudes. During the observation period, both routes carried only New York area departures bound for points west. J80 was the busier of the two routes, averaging four flights per hour, while J64 averaged one flight per hour. Of the 17 flights observed on J80, seven were at/or above FL270 crossing V3, while one of the four flights observed on J64 was at/or above FL270 crossing V3.

J48: This route as published runs between Boston and Pulaski (PSK), Va., and is one-way southbound from Westiminister (EMI), Md., to PSK. All of the observed flights on J48, east of V3 and at the altitudes of interest, were southbound from New England with a destination of either DCA or BAL. Of the 10 flights observed, nearly all were at FL220, and all were cleared via:

"...J48.JFK.JFK263..MXE056.MXE.V378..."

to either BAL or DCA. This cleared route provides for the descent and merging of the J48 arrivals to DCA/BAL from New England with the V3 arrivals to DCA/BAL from LGA/EWR, somewhere along the MXE056° radial. Two high altitude flights were observed to arrive each hour via J48, bound for DCA or BAL.

J6-8-42: Since the DCA/BAL arrivals would have to be out of the high altitude structure by the time they reach this intersection in any case, traffic on J6-8-42 is not a factor affecting short-haul cruise altitudes.

E.2 Analysis of the Potential Conflicts with the "Swan Point to Robbinsville" Short-Hauls

Table 6-4 summarizes the observed potential conflicts for those 7NP..RBV short-hauls wanting higher altitudes. The types and frequency of observed potential conflicts with each of the high altitude routes is discussed below.

J6-8-42: Medium- and long-haul arrivals to LGA/EWR from points southwest of New York arrive typically via J6 to Charleston, W.Va. (CRW), then J8 to Casanova, Va. (CSN), then J8-42 to Newcastle, De. (EWT). Medium-haul arrivals from points south of New York typically merge with the southwest arrivals at CSN. All arrivals via this route at the altitudes of interest were bound either for LGA or EWR. Since the Newark arrivals turn north at EWT, bound for Yardley (ARD), they are not a factor inhibiting DCA..LGA short-hauls. Four to eight flights per hour were observed to arrival via J6-8-42, or via "Casanova direct New Castle*," bound for LGA. All of the LGA arrivals were observed to cross the Washington-New York center boundary at FL240 or FL250, but were soon cleared to descend and maintain 10,000 feet for merging with the low altitude arrivals via Woodstown (OOD). At New Castle (EWT), the reported altitudes in descent ranged from 10,000 feet to FL240, apparently reflecting some pilot discretion in selecting the Beginning-of-Descent (BOD) point.

J150: Two streams of J150 traffic were observed to use the altitudes of interest: northbound departures out of the Washington area, and LGA arrivals from the south. Since the northbound J150 departures leave the Washington area in-trail with the short-haul departures via Swan Point, they are not a factor limiting the cruise altitudes of the short-haul departures.

Medium-haul arrivals to LGA/EWR from Florida and other points south can arrive the New York area via Gordonsville, Va. (GVE) and J150. Upon crossing the Washington-New York center boundary, these flights are at FL250 (or below) due to an altitude crossing restriction imposed by Letter-of-Agreement. These aircraft are subsequently cleared to descend to 10,000 feet and merged in-trail with the V123 short-hauls below. These aircraft are usually separated in-trail upon reaching Woodstown. About two aircraft per hour were observed to arrive RBV via J150.

J110: No traffic was observed on this dead-end segment (terminates just to the east at Coyle).

E.3 Discussion of the Two Traffic-Related Components of Controller Workload

To effect unambiguous assignment of control responsibilities to individual control teams, and to distribute the expected traffic workload somewhat uniformly among the control teams, the airspace

* The CSN..EWT direct routing can be used when Restricted Area R4001 is not in use.

is divided into a number of mutually exclusive control sectors. The size of each sector is limited in geography and altitude to keep the number of controlled aircraft which can enter the sector within the workload limits of its control team.

Sector workload can be thought of as being comprised of two basic components, one due to "handles" and the other due to "conflicts":

1. <u>"Handles Workload"</u>: Each aircraft handled by an air route control sector creates workload, whether or not it is conflict-free and whether or not any additional ATC clearances are required for it. This workload includes transfer-of-control from the preceding sector (or "in-bound handoff"), monitoring the progress of the aircraft through the sector, and transfer-of control to the next sector (or "out-bound handoff"). This workload is generally assumed to grow linearly with the number of handles (N).

2. <u>"Conflicts Workload"</u>: Each aircraft in-bound to, or operating within a sector, is a potential conflict for any other aircraft in-bound to, or within, the sector. If the conflict materializes (e.g., if in the controller's judgement, both horizontal and vertical separation can be lost, given current clearances), then the controller must conceive of an appropriate clearance revision, perhaps coordinate it with another sector, and subsequently issue a revised clearance to one or more of the aircraft involved. This process of conflict prediction, clearance revision/coordination, and subsequent clearance issuance constitutes an additional workload factor which is generally assumed to grow with the square of the number of handles (N^2).

The possible effects of allowing short-hauls into the high altitude structure are discussed in these terms in Section 6.

APPENDIX F

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